Construction of Grout-Impregnated Fabric-Reinforced Pipes

By Robert Nicholls,[1] Fellow, ASCE

Abstract: A method is evaluated for constructing pipes by injecting grout between an inner tube that can be inflated and an outer tube comprising a reinforcing mat in a fabric envelope. The mat is open-textured to allow easy impregnation by the grout and is sufficiently rigid to govern the wall thickness of the hardened pipe. The fabric envelope is permeable to water but impermeable to cement. Excess water is forced through the fabric by inflating the inner tube, carrying with it the grout, which lodges in the mat to harden, after which pressure is removed. Cyclic pressure is applied to simultaneously prestress the fabric and densify the grout. Fabric properties and the impregnation mechanism are described. Pipe ring stiffnesses are measured by the three-edge bearing test as a function of grout composition and pressure processing parameters. Potential applications include trenched and submarine pipes and tunnels, culverts, rock tunnel liners, and underground tanks.

Introduction

A pipe construction method is evaluated consisting of the following steps Fig. 1).

1. Unreel a lay-flat tube into a trench. The tube consists of three layers [Fig. 2(*a*)]: an inner plastic inflation tube, a plastic reinforcing mat, and an outer filter fabric shell. Clamp the ends over rigid disks, one of which has an inflation hose attached. Worm-screw banding over polyvinyl chloride (PVC) pipe caps were used for laboratory test pipes [Fig. 3(*a*)].
2. Pump measured volumes of grout into the reinforcing mat through a sharp tube penetrating the outer fabric shell. Inject the grout at intervals of about 10 pipe diameters. For laboratory test pipes, the fabric was pierced with a knife to simplify inserting the tube into it. A peristaltic pump was used to inject calculated volumes of grout [Fig. 3(*b*)]. A low-pressure grout pump is suitable for field use.
3. Inflate the inner tube with water to about 10 psi at 10 or more pulses per minute [Fig. 4(*b*)] to distribute the grout to uniform wall thickness throughout the reinforcing mat.
4. Then inflate at lower frequency (about one cycle per minute) to dewater the grout and densify it by forcing excess water through the outer fabric shell.
5. Inject $CaCl_2$ solution or other accelerator [Fig. 4(*c*)] followed by several more inflation cycles to distribute the $CaCl_2$ and to continue dewatering. This step reduces the cement hardening time; $CaCl_2$ can also be mixed initially with the grout, if setting time permits.
6. Maintain constant inflation pressure at about 3/4 cyclic pressure, for about 4 hr to harden the pipe [Fig. 4(*e*)].

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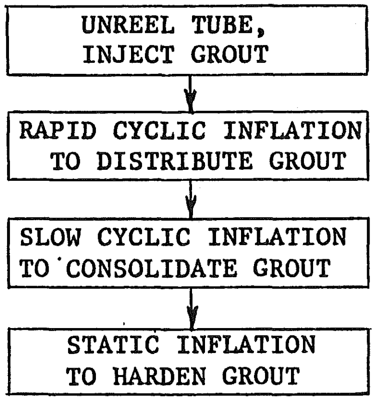

FIG. 1. Process Flowchart

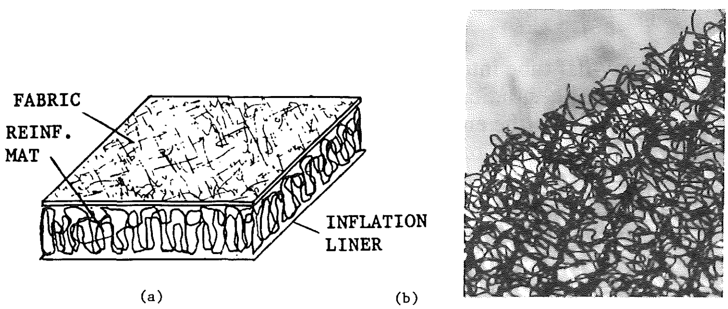

FIG. 2. (*a*) Pipe Wall Cross Section; (*b*) Enkadrain (Photo Courtesy of AKZO Industrial Systems Co.)

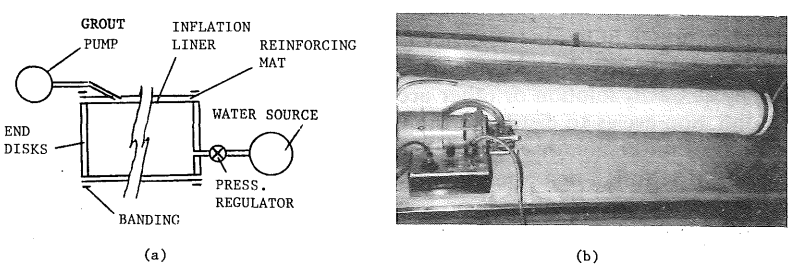

FIG. 3. (*a*) Pipe with Inflation Liner and Reinforcing Mat Banded over End Disks, and Water-Pressure Regulator for Inflating; (*b*) 4 in. Diameter Test Pipe during Pressurization, Peristaltic Grout Pump at Left, Line from Water-Pressure Regulator at Right

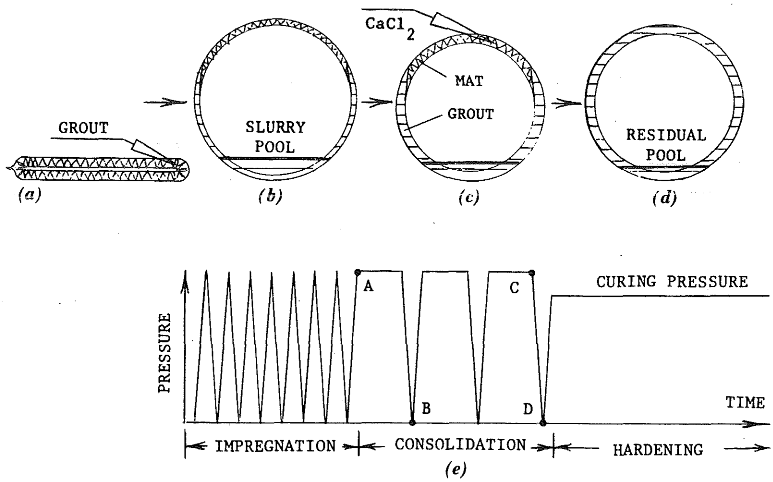

FIG. 4. Impregnation Sequence: (*a*) Grout Injection; (*b*) Inflation; (c) Deflation and Accelerator Injection; (*d*) Hardened Pipe; (*e*) Cyclic Pressurization

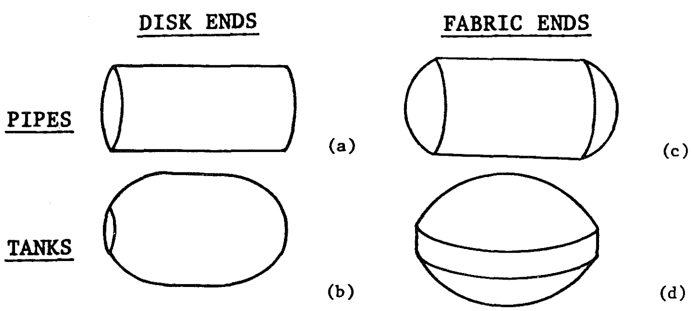

FIG. 5. Inflated Shapes: (*a*) Pipe Banded on Disk Ends; (*b*) Horizontal Tank Banded on Disk Ends; (c) Pipe Banded on Hoop Ends; (*d*) Vertical Tank Banded on Horizontal Hoop

The principal features are: (1) The forming of a rigid pipe by pumping grout into a reinforcing mat and pressurizing it to force water but not cement through the encasing fabric; (2) cycling of the pressure to repeatedly stretch the fabric, allowing grout to flow to produce a dense wall of roughly uniform thickness, prestressed by the fabric shell; (3) rapid hardening of the pipe by impregnating the grout with a cement accelerator.

Cyclic inflation distributes grout throughout the reinforcing mat, similar to resin-transfer molding in reinforced-plastics manufacture. Subsequent static inflation dewaters and densifies the grout and prestresses the fabric shell.

Objective and Potential Advantages

The objective is a preliminary feasibility study of a pipe-construction method. This paper describes the materials, impregnation mechanism, system requirements, and a feasibility study with test results for grouts having three fiber-reinforcement contents. Figs. 1–7 describe the production and

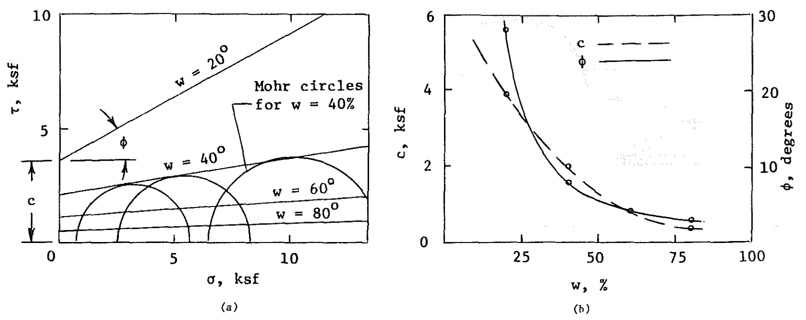

FIG. 6. Values of c and ϕ of Basic Mix at Various Water Contents Determined from UU Triaxial Tests: (*a*) Triaxial Test Results; (*b*) c and ϕ versus Water Content of Grout

material behavior during production. Figs. 8–11 give some test results for predicting feasibility. Fig. 12 describes pipe tests and Fig. 13 shows results of three-edge bearing tests.

Potential advantages are: (1) The reduction of costs, particularly for underground and submarine pipes. (2) The reduction of pipe transportation and handling. A 2 in. thick 5 ft diameter concrete pipe requires a shipping volume of about 20 cu ft and weight of about 400 lb/linear ft of pipe. The corresponding shipping volume and weight of a lay-flat fabric roll, to be inflated and impregnated with grout at the site, are 2.6 cu ft and 4.5 lb per linear ft of pipe. (3) The enabling of self-alignment of trenched and submarine pipes by inflation, and circumferential prestressing of the fabric shell by inflation. (4) The permitting of the use of narrower trenches. To allow all-weather construction, without dewatering, by eliminating the need to fit pipe sections together in a trench. (5) In submarine pipes, the permitting of ease of handling by pumping grout into a lay-flat tube as it is being reeled off of a barge. (6) The reduction of the pipe bedding cost by simply jetting dredged sand under and around the inflation-aligned pipe, instead of having to provide carefully graded and aligned bedding, as for submarine tunnel constuction methods that use connected rigid tube sections. Inflation pressure aligns the pipe, producing gradual curves vertically and horizontally. (7) For making large drainage culverts, opened by sawing away the two ends. Backfilling and compaction could be completed during inflation, to provide a stiffening soil or flowable cement–fly ash fill encasement to reduce the required pipe wall thickness. (8) In rock tunneling, to reduce costs of dewatering and of grouting overcuts, by unrolling the tube into the tunnel, pumping grout into it to form the walls, then pressure grouting the cavities between the hardened tube and the overcut tunnel. (9) The elimination of some of the requirements of precast concrete pipes; i.e., bell-and-spigot joints and rubber gaskets, beveled spigot ends for long radius curves, and cathodic or other protection for corrosion control of prestressing wire.

Prior Work

Because mortar-reinforcing fabrics may cost 30–100 times as much per unit volume as the mortar, there is economic incentive to find simple production methods to fully utilize fabric capabilities. Methods of incorporating reinforcing fabrics with mortars have included: (1) Screeding dry mortar

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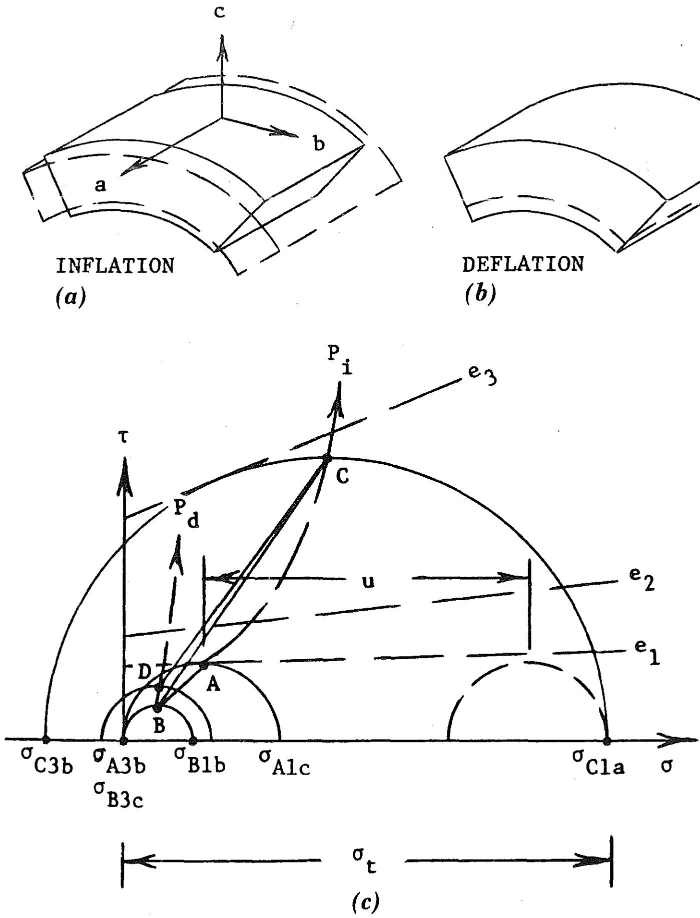

FIG. 7. Pipe-Wall Distortion during Pressure Cycling: (*a* and *b*) Coordinate System and Distortion Sequence; (c) Three-Dimensional Effective Stress Path

into the fabric followed by wetting and compacting; and (2) spreading wet mortar slurry into the fabric, then dewatering and compacting.

Alford (1985) described a process for pressing fibers into a cement slurry. Schupack (1986) pressed reinforcing fabric into cement slurry, in molding trays and on continuous rolls. Currie et al. (1986) formed composites by forcing cement slurry into oriented strands. Tesch (1985) layed wet cement between two fabric layers followed by needling the fabric layers together through the cement before it set. Walton and Majumdar (1980) used a spray-suction technique to spray 50 mm long aramid fibers and a cement slurry simultaneously from separate nozzles into a mold to a depth of 10 mm. Nicholls (1982) constructed pipes and tanks by placing inflatable plastic bags within a multilayer envelope of fabric already embedded with dry mortar, inflating the bag and then wetting the fabric from outside to harden the mortar. Nicholls (1984) spread dry mortar into fabric layers that were then supported on an inflated membrane and wetted to form a concrete dome

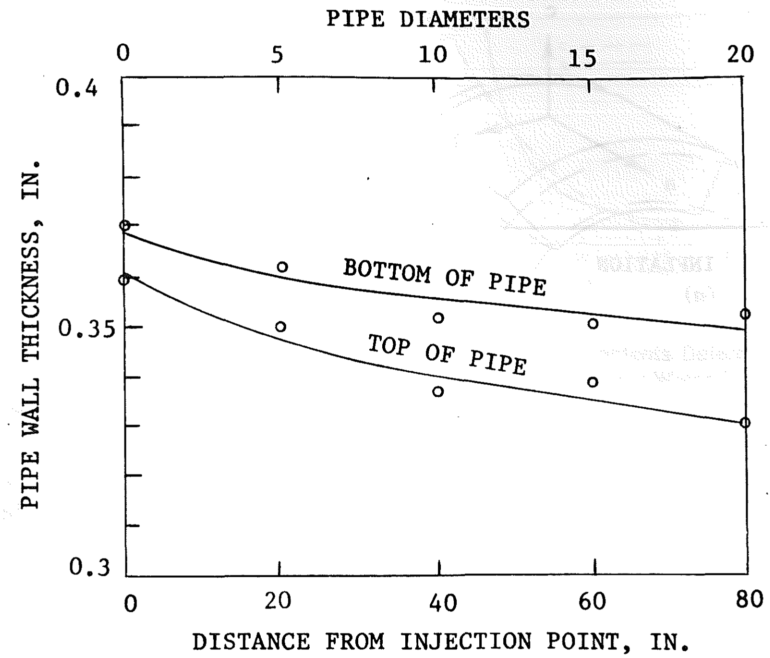

FIG. 8. Pipe-Wall Thickness versus Distance from Injection Point after 20 5 sec Pressure Cycles at 10 psi using Base Mix in 4 in. Diameter Pipe

in situ. Nicholls (1988) described a continuous-production method for screeding dry mortar into a loose three-dimensional fabric, then wetting and compacting, followed by compacting on a roll for storage and shipping. Nicholls (1990) made folded-plate structures by using reinforcing consisting of a central polypropylene fabric between two mineral wool faces such that the polypropylene provided a low modulus hinge for folding the hardened laminate, and the mineral wool provided high-modulus faces for stiffening against buckling.

All these methods involve pressing fabric into a slurry or spreading wet or dry mortar into the fabric. None involves pumping grout into fabric and pressing excess water out of the fabric, leaving the grout lodged in the reinforcing, which is the method used here.

Pipe Production

Fig. 2(*a*) shows a pipe wall cross section. Fig. 2(*b*) shows the geometry of a 0.4 in. thick reinforcing mat Enkadrain, made by AK20 Industrial Systems Co., of Asheville, N.C. The Enkadrain, made of nylon, is heat-bonded to 4.3 oz/sq yd geotextile fabric. Fig. 3 shows laboratory equipment for making test pipes. Fig. 4 shows the grout-distribution and dewatering sequence. Figs. 4(*a–d*) show cross-section changes during production, with changes in pipe diameter and wall thickness exaggerated. Fig. 4(*e*) shows cyclic inflation for grout impregnation, consolidation, and hardening. The points A to D correspond to Mohr circles A to D in Fig. 7(*c*), described later.

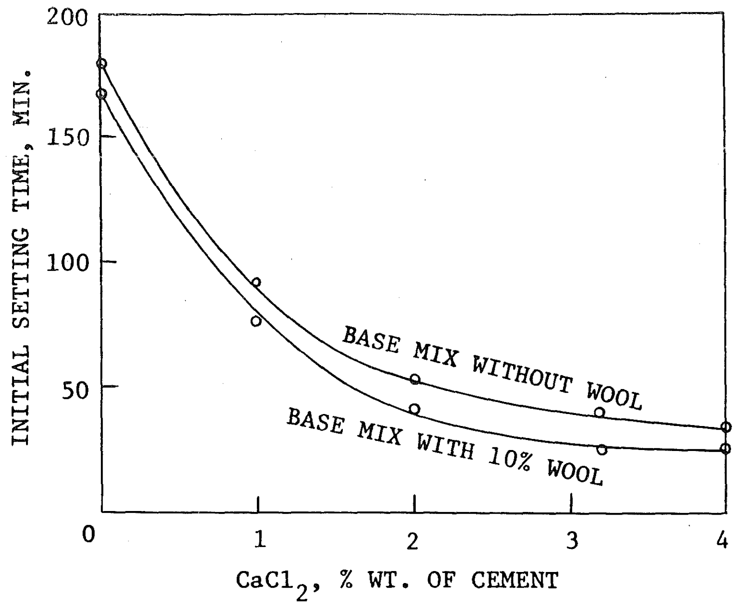

FIG. 9. Initial Setting Time of Base Mix versus $CaCl_2$ Content, Using Vicat Needle Test

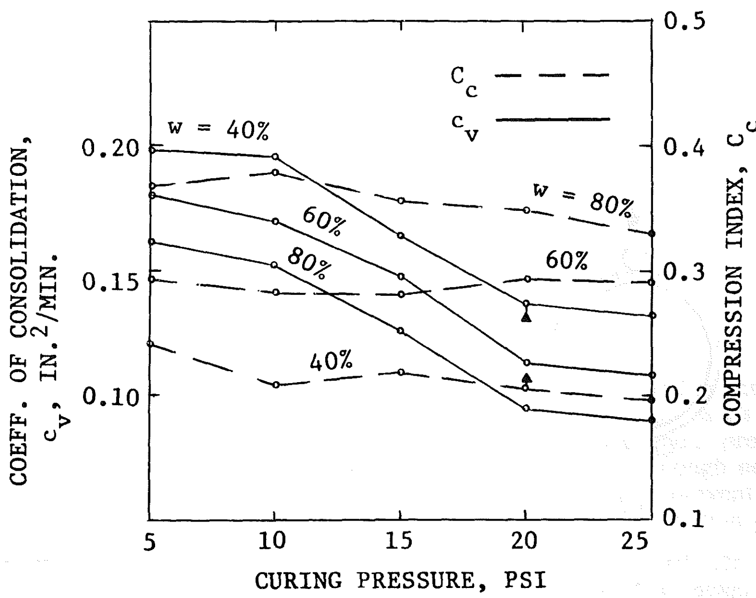

FIG. 10. Consolidation Coefficient c_v and Compression Index C_c of Base Mix versus Initial Water Content and Curing Pressure

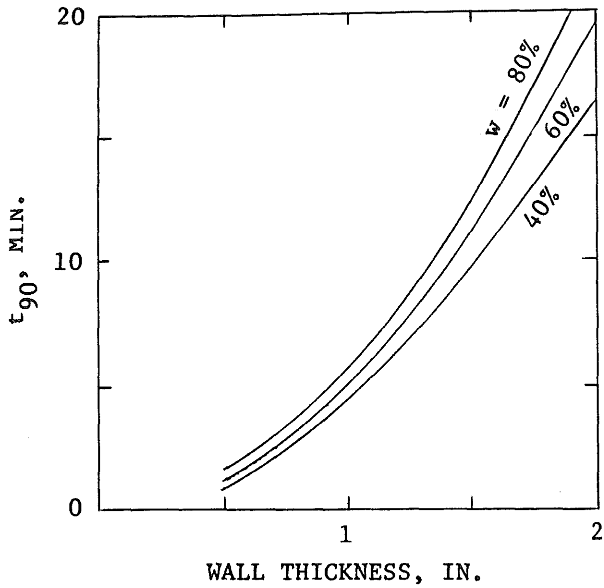

FIG. 11. 90% Primary Consolidation Time versus Wall Thickness of Base Mix at 10 psi Consolidating Pressure

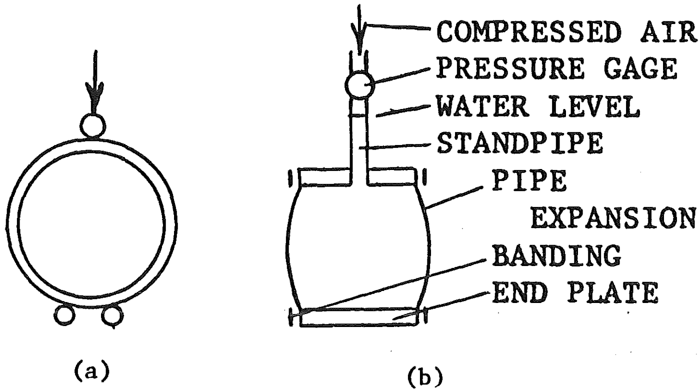

FIG. 12. (*a*) Three-Edge Bearing Test; (*b*) Hydrostatic Pressure Test, Showing Standpipe for Measuring Volume Increase as Function of Internal Pressure

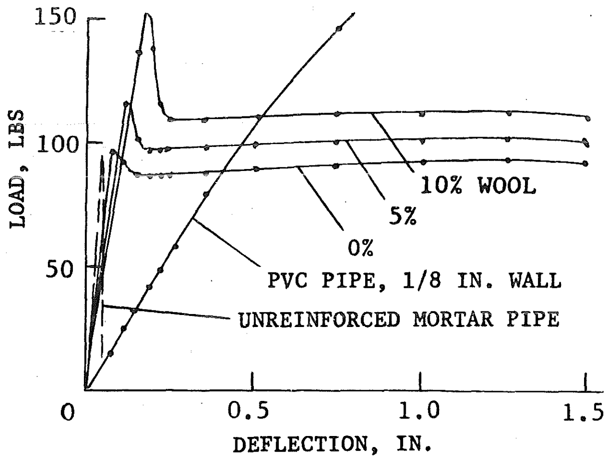

FIG. 13. Three-Edge Bearing Load-Deflection Plots for 4 in. Diameter Unreinforced Grout Pipe, Mat- and Wool-Reinforced Grout Pipes, and PVC Pipe

Impregnation

After injecting measured volumes of grout into the fabric at intervals [Fig. 4(*a*)] the pipe is inflated with short pulses to distribute grout circumferentially and axially to a uniform wall thickness. The grout flows to knead and heal longitudinal cracks, which open due to fabric stretching. Short pulses distribute grout with minimum stiffening due to loss of water through the fabric shell; 20 pulses of about 5 sec at 10 psi were used to prepare test pipes. During each pulse, the fabric shell expands, the reinforcing mat compresses, and wet grout flows toward lower hydrostatic head (toward thinner wall sections), thereby nearly depleting the slurry pool at the bottom of the pipe.

Consolidation

After grout is distributed uniformly so that the inflation liner bears against grout over the full interior, longer pressure cycles are used to consolidate the grout. Five cycles of 1 min each at 15 psi were used to prepare test pipes. During this period $CaCl_2$ solution was injected to shorten the hardening duration.

Hardening

Constant pressure is maintained until the grout has hardened enough to resist the tensile force in the fabric shell. The required duration varies with amount of accelerator used. A pressure of 10 psi for 4 hr was used to prepare test pipes. Pressure during mortar hardening must be low enough not to leave wall cracks due to fabric expansion, but high enough to prevent wall buckling during hardening, typically 2/3 to 3/4 of peak impregnation pressure.

Shapes

Fig. 5 shows possible pipe and tank shapes. Fig. 5(*b*) is a horizontal cylindrical tank banded over rigid end disks. The barrel shape is obtained by cutting and sewing the fabric perimeter larger than the disk perimeter.

Fig. 5(*c*) is a horizontal tank or pipe having two fabric ends banded over rigid end hoops. Fig. 5(*d*) is a vertical cylindrical tank having fabric top and bottom banded over a single wall hoop. These shapes of underground tank would resist backfill pressures efficiently. The reinforcing mat and fabric shell can stretch to a shallow, doubly curved shape without wrinkling.

Impregnation Mechanism

Impregnation involves high-frequency inflation to distribute grout, then low-frequency inflation to consolidate it. Grout flows toward the thinner sections of wall least filled with grout. Water weeps through the lower fabric first. Weeping progresses upward as grout is squeezed into the unimpregnated part of the reinforcing mat. The inflation liner floats on the grout slurry pool until the entire wall has been impregnated.

Grout Flow

The critical hydraulic gradient i_c for upward grout flow is

$$i_c = \frac{G - 1}{1 + e} \quad \text{(1)}$$

where G = average specific gravity of the solids; and e = void ratio.

Example 1: Compute the required inflation pressure to distribute grout for uniform wall thickness in a 10 ft diameter pipe, given the mix in Table 1.

Solution: The average specific gravity of solids is $G = [2.7(1) + 2.5(1) + 2.8(0.1)]/(1 + 1 + 0.1) = 2.61$. The void ratio is $e = v_v/v_s = 1/(1/2.7 + 1/2.5 + 0.1/2.8) = 1.24$, where v_v = volume of voids (water); and v_s = volume of solids. From (1), $i_c = 1.64/2.24 = 0.73$. For flow from the bottom of pipe to top, the vertical flow component of hydraulic gradient i_a is

$$i_a = \frac{\Delta h}{\Delta d} = \frac{\Delta h}{10} \quad \text{(2)}$$

where Δh = hydrostatic head drop from bottom to top of pipe; and Δd = vertical flow distance.

Equating (1) and (2), Δh = 7.3 ft, or a required inflation pressure of 7.3(62.4)/144 = 3.16 psi at the bottom of pipe to produce a quick condition, i.e. 0.316 psi/ft of pipe diameter. Cyclic inflation pressures two to five times this value have worked well in 4 in. pipe to overcome flow resistance of the fibrous grout through the mat for approximately uniform wall thickness with less than 20 5 sec, 10 psi pressure pulses. This was determined by visually observing water exudation through the tops of pipes midway between injection points, and by measuring uniformity of wall thickness of hardened

TABLE 1. Grout Mix for Example 1

Component (1)	Specific gravity (2)	% by weight of cement (3)
Cement	2.7	1.0
Fly ash	2.5	1.0
Wool	2.8	0.1
Water	1.0	1.0

pipes, described later in Fig. 8. The required pressure may be due to flow impediment by the reinforcing mat and because as grout approaches uniform wall thickness most of the head drop occurs through the wall, not circumferentially, to produce grout flow.

Example 2: Find the required grout-injection volume for the 10 ft diameter pipe, given the values in Table 2.

Solution: For 8 psi inflation pressure at the bottom of the 10 ft diameter pipe, the hoop tension is within (8 psi) (60 in. radius) = 480 lb/linear in., and the tensile safety factor of the fabric shell is 700/480 = 1.46. The expanded shell diameter is (10 ft) (1 + 480/12,000) = 10.4 ft. The compressed-mat thickness is (2.4 in.) (1 − 8/20) = 1.44 in. = 0.12 ft. The wall volume is then approximately $\pi(10.4)(0.12) = 3.92$ cu ft/ft of pipe. Assuming a 0.8 psi base pressure, the required grout volume before dewatering is $3.92/[1 - 0.35(\log 8 - \log 0.8)] = 6.03$ cu ft/ft. Adding 10% volume for a residual slurry pool [Fig. 4(*d*)] gives a required grout volume of 6.63 cu ft/ft of pipe. The extra 10% ensures that inflation pressure is carried by the grout around the full perimeter, not by the reinforcing mat, so that all grout is uniformly dewatered and densified.

Grout Consolidation

Fig. 6 shows the increases in grout cohesion c and internal friction angle ϕ as the grout dewaters, determined from UU (undrained unconsolidated) triaxial tests; 1.28 in. diameter by 2.8 in. high specimens molded to standard Proctor density in a miniature Harvard compaction apparatus were tested at 5, 15, and 45 psi confining pressures. Fig. 6(*a*) shows the triaxial test results, and Fig. 6(*b*) plots c and ϕ versus grout water content w based on weight of cement. These test values would bracket the range of c and ϕ values during the wall-consolidation phase; c values ranged from 0.4 ksf to 3.5 ksf and ϕ values ranged from 3° to 28° [Fig. 6(*b*)]. The grout is characterized by higher ϕ values than most soils of similar particle-size range. The sharp increases in both c and ϕ values at a water content below about 40% indicate the significant rise in resistance to plastic flow as the grout dewaters. This led to the practice of applying rapid cyclic loading at high pressure (5 sec at 10 psi) to distribute grout to approximately uniform wall thickness before much dewatering could occur.

Fig. 7(*a*) shows the pipe-wall distortion during inflation and deflation. The solid lines show undistorted shape. On inflation, the fabric shell expands and grout dewaters, causing expansion in the b direction, contraction in the c direction, and slight expansion in the a direction, with isotropic fabric, because a-direction tension is only half b-direction tension, and due to the opposing effect of fabric Poisson ratio in the ab plane. That is, $T_c = pr$; and $T_a = \pi r^2 p/2\pi r = pr/2$, where T_c and T_a = circumferential and axial

TABLE 2. Design Values for Example 2

Property (1)	Value (2)
Curing inflation pressure	8 psi
Fabric shell tensile strength	700 lb/linear in.
Fabric shell tensile modulus	12,000 (lb/in.)/(in./in.)
Reinforcing mat thickness	2.4 in.
Reinforcing mat compressive modulus	20 psi/(in./in.)
Grout compression index (C_c)	0.35 (as from Fig. 10)

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tension, respectively; p = inflation pressure; and r = pipe radius. This 2:1 ratio between circumferential and axial stresses, which is independent of radius, contributes to the kneading action. During deflation, a and b axis tensile strains return to nearly zero and some residual c axis compression remains due to dewatering.

Fig. 7(b) shows the three-dimensional effective stress path in the grout during cyclic inflation. The A and B Mohr circles correspond to inflation, in Fig. 7(a), and deflation, in Fig. 7(b). This resembles the stress path for consolidation in a cyclic-loaded triaxial shear test. The solid circles are effective stress circles. The total stress circle is shown only for circle A (dashed circle). The offset pressure (u) is pore pressure; u is zero at the filter fabric and maximum at the inflation liner. Its value depends on inflation rate, wall thickness, location within the wall, and instantaneous state of dewatering.

In Fig. 7, ABCD = effective stress path with cyclic inflation; a,b,c = local rectangular coordinate axes; d = deflation; $e_1 - e_n$ = Mohr-Coulomb failure envelopes as the grout dewaters with each inflation; i = inflation to the point of grout shear failure (Mohr circle tangent to failure envelope); P = effective stress path; t = total applied pressure; u = pore pressure; σ = normal stress; τ = shear stress; and 1,2,3 = major, intermediate, and minor principal effective stresses.

The Mohr circles correspond to points A to D in Fig. 4(e), and represent the following.

Circle A: Initial inflation for consolidation, when average pore pressure u through the wall is high. The effective normal stresses are σ_{A1c} and σ_{A3b}. Subscripts 1 and 3 designate maximum and minimum principal stresses; c and b designate stress directions shown in Fig. 7(a and b) and A designates the initial inflation, in Fig. 4(e); σ_{A3b} is zero because the wet grout cannot carry the tension caused by b axis elongation. During each inflation, radial (c axis) stress increases and circumferential (b axis) stress reduces, increasing deviator stress until failure occurs. With each inflation, the Mohr-Coulomb failure envelope, e_1, e_2, etc., moves upward due to grout dewatering and consolidation, in accordance with the Fig. 6 test results.

Circle B: Initial deflation, when maximum principal compressive stress is in the b direction (σ_{B1b}) due to shortening of the fabric shell perimeter, and minimum principal stress is in the c direction (σ_{B3c}).

Circle C: Final inflation, with pore pressure reduced to nearly zero (solid and dashed circles coincide), and the dewatered grout is capable of carrying some tension in the b direction (σ_{C3b}) due to the wool-fiber reinforcement.

Circle D: Final deflation before applying constant curing pressure. In accordance with Fig. 6 data, the residual compression and tension both increase as the fiber-containing grout becomes dewatered, leading to the increased size of circle D over circle B.

The dashed line P_i is the stress path for successive inflation cycles, and P_d for successive deflation cycles. The zigzag line ABCD is the effective stress path during cyclic inflation for consolidation. The kneading action due to cycling of circumferential (b axis) stress between tension during inflation and compression during deflation enables consolidation at lower maximum stress. The concave upward curve of path P_i corresponds to initial dewatering, with reduced average pore pressure u, followed by pronounced movement upward of the failure envelope e, shown by the Fig. 6(b) data.

After curing and final deflation, not shown in Fig. 7(c), the maximum principal grout stress is circumferential (b axis) due to fabric prestress being transferred to the hardened grout. Grout may thus harden with a low tensile stress in the circumferential (b) direction, and return to compression due to minor prestress provided by the fabric shell when inflation is removed.

MATERIALS

Fabrics

The outer fabric [Fig. 2(a)] must be permeable to water but not to cement (10–20 μm sizes) and must stretch slightly during impregnation, allowing movements of the wall during cyclic inflation to increase grout density by kneading. The reinforcing mat must be permeable to grout. For uniform wall thickness, it must also be sufficiently rigid not to compress unduely by pressure from the inflation liner. One suitable material for both layers is Enkadrain [Fig. 2(b)] marketed as a geofilter, which is a three-dimensional rigid nylon mat heat-bonded to polyester nonwoven filter fabric. The mat, available in several densities and thicknesses, is open enough to pass grouts containing 1/8 in. long mineral-wool reinforcing fiber and compresses by less than half of its thickness under 7 psi. Several mats 0.4–0.8 in. thick can be layered inside of a single filter fabric to form the thickness-controlling reinforcement.

In the hardened pipe the mineral wool provides tensile stiffness and strength while the fabric shell and reinforcing mat provide postcracking toughness. The mat also provides sufficient pseudoplasticity to the otherwise brittle grout for buried pipes to be designed as flexible, rather than rigid, pipes, developing full passive earth pressure at their sides to reduce the required wall thickness (see the postpeak deformations, Fig. 13).

Grout

The grout used for tests was 1/1/0.1/1 by weight of cement/fly ash/mineral wool/water. This is called the base mix. Laboratory mixing was with a 1/2 in. electric drill and helical wire mix blade.

A consistency that pours like a thick milk shake works well, or a spread of at least 5 in. diameter flowing from a 12 fluid oz (2.62 in. diameter by 4.75 in. high) open-ended can when filled with grout and lifted off a glass plate or plastic sheet. Wetter grouts require longer pressurization to force excess water through the fabric. Drier grouts tend to give less-uniform wall thickness because their lower viscosities reduce grout mobility. Either a superplasticizer or about 5% of styrene-butadiene latex reduces viscosity and allows slightly drier mixes. Fly ash provides a low-cost mineral filler whose small spherical particles improve grout flowability and impregnation into the reinforcing mat. Delmarva Edgemoor Plant (ASTM Type F) fly ash was used. Fine sand can be used, but the mix is less flowable. In addition to being a high-modulus low-cost reinforcement, mineral wool serves as a thixotropic agent, preventing the settling of fines in the grout. At $250/ton, it costs about 2.5 times as much as portland cement. U.S. Gypsum Thermafiber mineral wool reinforcement, having a hydrophilic coating to facilitate dispersion in grouts, was used.

Inflation Liner

A 3 mil cross-laminated two-ply polyethylene film having two edges taped together to form a tube served well for inflating test pipes. The film resists tearing after repeated expansion against the reinforcing mat.

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System Requirements

System requirements can therefore be summarized as: (1) Adequate pressure to move grout through the mat to a uniform wall thickness; (2) grout consolidation time less than initial setting time of cement; (3) fabric tensile strength adequate to resist inflation pressure; (4) fabric porous to water but not to cement; (5) reinforcing mat open enough to allow free flow of grout containing the reinforcing fiber; and (6) inflation film tough enough to remain watertight with cyclic inflation.

Exploratory Tests

Some preliminary tests and analyses indicated that these requirements could be met. Consider the first two system requirements, illustrated in Figs. 8–11.

First, pressure to distribute grout to uniform wall thickness: As grout-injection points are spaced farther apart, more inflation pulses and/or greater pressure are required to produce uniform grout thickness along the pipe. At large spacings the grout dewaters too much to be uniformly disbursed, regardless of number of pulses. Fig. 8 shows the variations in wall thicknesses at the top and bottom of a hardened pipe, obtained by measuring sawed sections with a vernier caliper, versus distance from injection point. The base mix and base pressure regime described later, in the section headed "Pipe Test Parameters," were used. The less than 6% reduction in top-of-pipe wall thickness at 20 diameters from the injection point suggests that injection point spacing would not likely be a critical constraint in grout-inflated pipe construction.

Second, consolidation time less than initial setting time: It is desirable to complete consolidation dewatering before initial set in order to obtain full grout strength, and to still accelerate hardening in order to reduce required static inflation time. One way is to inject $CaCl_2$ near the end of pressure cycling; $CaCl_2$ is acceptable because there is no steel reinforcing to corrode. Test results in Figs. 9–11 show approximate consolidation and hardening periods for design. Fig. 9 gives the initial set time of the base mix (see "Pipe Test Parameters") versus $CaCl_2$ contents, measured by the Vicat needle test, i.e. 25 mm in 30 sec., by American Society for Testing Materials (ASTM) test method D191-82. Fig. 10 shows the coefficient of consolidation c_v and compression index C_c of the base mix measured in 2.5 in. soil consolidometers according to ASTM D2435-70; w is the grout water content, by percent weight of cement. To determine if consolidation test results were influenced by cement hydration during the test period, the $w = 40\%$ at 20 psi mix was duplicated containing Sika Plastiment retarder at the rate of 1 oz per 10 lb of cement, shown by the triangle symbols in Fig. 10. The triangles lie close enough to the unretarded test data to indicate that results were not appreciable affected by cement hydration during the test period. These coefficients of consolidation are an order of magnitude greater than those of most soils having a similar range of particle sizes, and indicate that required consolidation times should offer no significant obstacle to pipe production. For example, Fig. 10 results were used to compute 90% primary consolidation times in Fig. 11, from $t_{90} = T_{90}H^2/c_v$, where t_{90} = time for 90% primary consolidation; T_{90} = dimensionless time factor (= 0.848); H = maximum flow distance to a free-draining surface (= pipe wall thickness); and c_v = coefficient of consolidation from Fig. 10. The retarded sample also had less than 4% secondary consolidation, further assuring easy attainment of nearly all consolidation before initial set of cement.

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If accelerator is mixed with the grout instead of injected separately near the end of pressure cycling, one can use Figs. 9 and 11 to select a maximum accelerator level to prevent initial set before 90% primary consolidation. For example, consider a 2 in. thick wall. From Fig. 11, $t_{90} \approx 20$ min. Assume that an additional 20 min is required to mix, inject, and distribute the grout, for a total of 40 min before initial set should occur. Then from Fig. 9, at 40 min, $CaCl_2 \approx 2\%$ by weight of cement.

Experimental Program

Pipe Test Parameters

The following test values were selected for observing pipe structural behavior, based on some preliminary tests and the results of Figs. 8–11.

1. Pipe diameter: 4 in.
2. Pipe length with single injection point at one end: 18 in.
3. Grout mix: 1/1/0.1/1 by weight of cement of cement/fly ash/mineral wool/water, respectively.
4. Grout volume: 10% excess slurry pool, as calculated in example 2.
5. Reinforcing mat thickness: 0.4 in.
6. Inflation: 20 impregnation pulses at 10 psi for 5 sec each, then five consolidation cycles at 15 psi for 1 min each, then static curing at 10 psi for 4 hr.
7. $CaCl_2$ injection: 30% solution, 10% by weight of cement (3% $CaCl_2$ by weight of cement), injected at the beginning of inflation for consolidation.

The fly-ash level that maximizes flow at a given water content could be determined by the method of normalizing flow table results (ASTM: "Standard" 1974) developed by Joshi and Nagaraj (1990). But for these tests a fly ash/cement weight ratio of 1 was arbitrarily chosen.

Pipe Preparation and Tests

Fig. 3(*b*) shows the peristaltic pump metering grout through the sharpened tube into the reinforcing mat of one pipe. Water was used for inflation instead of air so that pressure could be changed quickly. External three-edge bearing tests and internal hydrostatic pressure tests (Fig. 12) are typically used to evaluate buried pipes ("AWWA" 1984), and ASTM Designation C497-88.

Three-edge ring bending stiffness: Ring stiffnesses *EI* from the three-edge test were calculated from (Spangler and Handy 1982)

$$EI = 0.149 \frac{Wr^3}{\Delta y} \quad \text{(3)}$$

where E = pipe-wall modulus; I = moment of inertia of wall ($t^3/12$); t = wall thickness; W = three-edge load per unit length of pipe; r = mean pipe radius; and Δy = vertical deformation of pipe ring.

Hydrostatic pressure test: The liner and standpipe [Fig. 12(*b*)] are filled with water and the volume change is observed by the drop of water level in the standpipe as a function of air pressure in order to compute tensile stiffness of the hoop and effective prestress (highest pressure for which there is zero hoop strain). (These will be reported elsewhere for lack of space here.)

TEST RESULTS AND INTERPRETATION

The test results in Fig. 13 and Tables 3 and 4 are for evaluating construction feasibility, not to develop predictive models based on grout composition and inflation process parameters.

Three-Edge Ring Bending Stiffness

Fig. 13 compares the measured three-edge bearing load-deformation plots after seven-day moist curing at 20°C for 3 in. long pipe sections formed to approximately 4 in. inside diameter (ID) and 0.28 in. wall thickness (a single layer of reinforcing mat) having 0, 5, and 10% mineral wool by weight of cement, with that for an unreinforced pipe of similar size (dashed line in Fig. 13), and for a 3 in. long 4 in. ID 1/8 in. wall PVC pipe. The initial tangent slope of the load–vertical deflection plot was used for calculating *EI* values from the three-edge bearing test. Load rate was 0.1 in./min. Test results on three specimens sawed from the same pipe were averaged for each plotted point. The unreinforced pipe was cast instead of inflated, and had a 4 in. outside diameter (OD) instead of 4 in. ID. The graph shows vertical deformations of the 4 in. grout pipes up to 1.5 in., at which point reversal of curvature appeared at the tops of several pipes. Fig. 13 shows that: (1) The load-deformation plot is more linear, like a proving ring would be, for the PVC pipe than for the fabric-reinforced grout pipes; (2) the initial tangent stiffness of grout pipes is decreased by the presence of the reinforcing mat, and decreased slightly by increasing the wool reinforcing content; (3) load-deformation plots for the inflated pipes rise rapidly to a peak load, when cracking is heard, located usually near the load points but sometimes near the 90° points. The load then falls abruptly to some level and remains quite constant to at least 1.5 in. deformation of the 4 in. diameter pipes. The peak load increases with increasing wool content, and is more sensitive to wool content than is the load at large deformation, which may depend predominantly on the reinforcing mat.

TABLE 3. Ring Stiffnesses of Pipes Prepared at Different Impregnation Pressures

Impregnation pressure (1)	Ring stiffness lb-in. (2)
20 cycles at 10 psi	1,081
10 cycles at 3 psi, then 10 at 10 psi	1,059

TABLE 4. Comparisons of Two 4 in. Diameter Pipes Impregnated at 20 Cycles of 4 psi and at 20 Cycles of 20 psi Pressure

Impregnation pressure (psi) (1)	Constant 4 hr hardening pressure (psi) (2)	Average internal diameter (in.) (3)	Average wall thickness (in.) (4)	Ring stiffness *EI* (lb/in.) (5)
4	3	4.02	0.38	942
20	12	4.10	0.34	1,164

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Effect of Continued Cyclic Inflation at Increased Pressure after Attaining Partial Impregnation

On 4 in. diameter pipes cycled to 10 psi, if after little weep water appears with each pressure pulse, the cyclic pressure is doubled, renewed weeping appears along longitudinally oriented cracks, caused by fabric stretching due to increased hoop tension. These cracks then apparently fill in after repeated pressure cycles, as evidenced by reduced weeping.

Table 3 compares ring stiffness of identical 4 in. diameter 0.28 in. thick pipes containing 5% wool by weight of cement prepared with 20 cycles at 10 psi impregnation pressure and prepared with 10 cycles at 3 psi followed by 10 cycles at 10 psi. Each value in Table 3 is calculated by (3) from the average of test results on three sections sawed from the same pipe. The small increase from 1,059 lb-in. to 1,081 lb-in. ring stiffness suggests that initial 3 psi impregnation cycling accomplished almost the same result as 10 psi impregnation for all 20 cycles.

Possible Prestressing Contribution

Table 4 compares the ring stiffness, measured by three-edge bearing and computed by (3), of two 4 in. diameter pipe sections identical to those presented in Table 3 except that one was prepared with 20 cycles of 4 psi impregnation pressure and the other with 20 cycles of 20 psi impregnation pressure. The higher cyclic pressure produced an (1,164 − 942)/942 = 24% increase in ring stiffness. It is not known how much of the increased ring stiffness with higher impregnation pressure can be attributed to fabric prestressing and how much to increased wall-grout density. Each value is the average of tests on three sections sawed from the same pipe.

COMMENTS

Practical Limitations

High wool content increases postcracking ring stiffness (Fig. 13), but reduces mortar flowability. There would be an economic trade-off between providing required stiffness with added mineral wool or other high-modulus reinforcement, which increases the risk of nonuniform wall properties, and providing stiffness with a thicker wall, which requires greater cost in grout and reinforcing mat. Adding reinforcement increases postcracking modulus E in (3), whereas adding wall thickness increases moment of inertia I.

Major limitations are the lack of simple methods for examining, testing, and quality assurance of pipes. Field hydrostatic pressure tests, like the laboratory test, would be inexpensive to perform on long pipes, but if volume change indicated unacceptable wall bulging, the location of the weak section could not be determined from that test.

Continuous-strand reinforcing mat [Fig. 2(*b*)], which is rigid enough to assure uniform wall thickness, does not easily fold 180° to form lay-flat tubing. Open-braided interlock fabrics fold more easily, but are many times more costly, especially when adequately rigid to maintain nearly uniform wall thickness.

Although inflation liners have not been punctured in laboratory pipe production, they may be by excessive inflation against the rough mat, or by inadvertently inserting the mortar-injection tube through the liner when the pipe is too highly inflated. This requirement for construction care may reduce the method's usefulness.

The longitudinal seam in the fabric shell is rather awkward to sew with

TABLE 5. Reproducibility of Wall Thicknesses and Ring Stiffnesses of Four 3 in. Long Rings Sawn from Single Test Pipe

Ring Stiffness		Wall Thickness[a] (in.)				
Specimen (1)	lb-in. (2)	Top (3)	Bottom (4)	One side (5)	Other side (6)	Average (7)
1	1,067	0.34	0.39	0.36	0.35	0.360
2	1,058	0.33	0.40	0.35	0.37	0.363
3	1,080	0.33	0.36	0.34	0.36	0.347
4	1,049	0.31	0.40	0.36	0.33	0.358

[a]By micrometer, 1 in. in from one end of each pipe specimen.

the reinforcing mat and inflation liner already inserted. The sewing technique can be improved with increased production. Narrow longitudinal lap joints in the mat were made by pressing overlapping portions of mat together very tightly so that they intertwine to nearly constant thickness.

In large culverts, strength and stiffness are important. In pipelines, impermeability is usually more critical. The inflation liner can serve as a permanent pipe liner. Submarine tunnels, requiring impermeability to external pressure, would require an external bentonite seal, film envelope, or other seal membrane.

Conclusions

This is a proof-of-construction concept study. Grout-impregnated fabric-reinforced pipes were tested to explore constructability and to evaluate pipe stiffness as a function of grout composition and pressure regime during processing. Major concerns are the difficulty of inspection and the uncertainty of quality control, although the uniformity of the wall thicknesses and ring stiffnesses of small laboratory test sections summarized in Table 5 is encouraging.

The following observations are based on results from limited testing.

Ring stiffness of hardened pipes increased by only 2% when 20 cycles at 10 psi impregnation pressure were used instead of 10 cycles of 3 psi followed by 10 cycles at 10 psi (Table 3).

Ring stiffness increased approximately 24% by increasing impregnation pressure from 4 psi to 20 psi (Table 4).

This pipe construction method can be further evaluated inexpensively on small pipes, using pipe-stiffness and strength measurements as functions of material compositions and production procedure.

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Appendix I. Conversion to SI Units

To Convert	To	Multiply by
cu ft	m^3	0.0283
ft	m	0.3048
in.	m	0.0254
lb/ft	N/m	14.59
lb/in.	N/m	175
lb/sq ft	Pa	47.88
lb/sq in.	Pa	6.895

Appendix II. References

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Appendix III. Notation

The following symbols are used in this paper:

ABCD = points on effective stress path with successive inflation and deflation;
a,b,c = local rectangular coordinate axes;
C_c = compression index;
c_v = coefficient of consolidation;
d = deflation;
E = pipe-wall modulus;
e = void ratio;
$e_1 - e_n$ = successive Mohr-Coulomb failure envelopes as grout dewaters with each pressure cycle;

G = specific gravity;
H = maximum drainage path length;
I = moment of inertia of wall ($= t^3/12$);
i = inflation to point of grout shear failure (Mohr circle is tangent to failure envelope);
i_a = hydraulic gradient;
i_c = critical hydraulic gradient;
P = effective stress path;
p = inflation pressure;
r = mean pipe radius;
T_a = axial tension;
T_c = circumferential tension;
T_{90} = dimensionless time factor for 90% primary consolidation;
t = total applied pressure;
t = wall thickness;
t_{90} = time for 90% of primary consolidation;
u = pore pressure;
W = three-edge load per unit length of pipe;
w = water content of slurry;
Δd = flow distance;
Δh = hydrostatic head drop;
Δy = vertical deformation of pipe ring;
σ = normal stress;
τ = shear stress; and
1,2,3 = major, intermediate, and minor effective principal stresses, respectively.