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STRENGTH-TO-WEIGHT AND HYDRAULIC FLOW CHARACTERISTICS OF SMOOTH-CORE CORRUGATED PE PLASTIC PIPE

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U.S. market demand continues upward for standard corrugated-wall polyethylene (PE) pipes of 305mm (12 in.) diameter and larger in land drainage applications. These corrugated plastic pipes are also extensively used in culvert applications previously dominated by concrete and corrugated steel pipe (Fouss and Reeve, 1987). All three types of pipe are comparably priced, but the light-weight corrugated plastic pipes are easier to handle and less costly to transport and install for many applications, and provide superior service life in corrosive environments. Despite these significant advantages, the limiting characteristics of reduced flow capacity and the less than optimum resistance to deflection under soil loading with the standard corrugated-wall PE, especially for the larger diameters, have kept the corrugated plasitic pipes from achieving the full engineering use potential often inherent to the corrugated type of structural design configuration.

Recent advances in manufacturing technology have made it possible to economically produce a smooth-core corrugated plastic pipe by thermally bonding a smooth interior core to an external corrugated shell (Fig. 1). This combination of the desirable hydraulic flow of smooth-walled pipe with the exceptional strength-to-weight ratio of corrugated pipe greatly improves performance in land drainage and culvert applications and opens up major new applications such as storm sewers. The smooth interior core also permits the use of deeper corrugations to significantly increase the structural strength of the pipe without diminishing its resistance to stretch under axial loading. Still other benefits accrue as a result of advances in structural performance of high density polyethylene resins in piping applications and improved corrugated pipe joining systems. Thus, the new smooth-core corrugated plastic pipe has the potential to become the "I-Beam" of the plastic piping industry as a high strength-to-weight ratio engineered pipe capable of efficiently and economically meeting stringent performance requirements of a wide variety of applications. New performance standards and specifications for the smooth-core corrugated product are now being developed by national authorities in the U.S. for land drainage, culverts, and for an increasing number of new applications including storm sewers, conduits, and others.

This paper presents analytical comparisons of strength-to-weight and hydraulic flow characteristics between smooth-core corrugated PE plastic pipe and other piping materials including, standard corrugated-wall PE,

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smooth-wall plastic (e.g., PE or PVC), concrete, and galvanized corrugated steel. Analytical procedures employed are described.

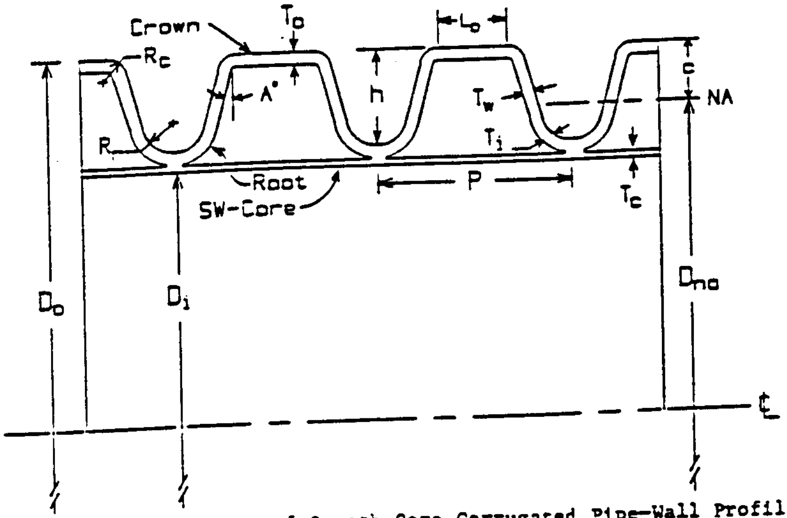

Fig. 1 Cross-Section of Smooth-Core Corrugated Pipe-Wall Profile with Definitions of Geometrical Terms and Dimensions.

The pipe-wall dimensional parameters shown in Fig. 1 are defined as follows:

A = angle of corrugation 'web'
Lo = length of 'crown' flat
To = corrugation 'crown' thickness
Tw = corrugation 'web' thickness
Ti = corrugation 'root' thickness
Tc = thickness of SW-'core'
h = corrugation depth
P = corrugation pitch

Rc = radius of crown fillet
Rr = radius of corrugation root
NA = neutral-axis of pipe-wall
c = distance NA from O.D. of pipe
Dna = neutral-axis diameter of pipe
Do = outside diameter of pipe
Di = inside diameter of pipe
℄ = center-line of pipe diameter

ANALYSIS OF PLASTIC PIPE STRENGTH

The structural strength of a plastic pipe was expressed as a function of its deflection resistance when loaded between parallel-plates. This pipe test method is required in ASTM Standard Specification F-667 for Large-Diameter Corrugated Polyethylene Tubing. The strength-deflection characteristic determined for a conduit tested by this method and defined as the "Pipe Stiffness", was expressed in units of applied load per unit length of pipe sample per unit of vertical deflection (flattening) of the pipe sample; i.e., (kg/mm/mm or kg/mm^2). The parallel-plate pipe stiffness was expressed mathematically in terms of geometrical, physical, and pipe-wall material properties of the conduit structure, as shown below.

$$\text{Pipe Stiffness} = (W/\Delta Y) = 53.6 * E * I / (Dna)^3 ,$$

where,

W = parallel-plaste load on pipe sample, kg/mm of pipe length
ΔY = vertical pipe deflection under parallel-plate load, mm
E = modulus-of-elasticity for pipe-wall material, kg/mm^2
I = moment-of-inertia of pipe-wall cross-section, mm^4/mm pipe length
Dna = diameter of pipe to the neutral-axis (NA) of pipe-wall, mm
53.6 = dimensionless constant related to angular position of parallel-plate loads on pipe circumference, and to convert from pipe radius to pipe diameter.

This formula applies for the linear range of deflection between parallel-plates for high-density PE plastic corrugated-wall pipe, which typically occurs from 0 to between 5 and 10% deflection of the inside pipe diameter (Fouss, 1973). At a specified pipe stiffness (W/ ΔY) for a regular corrugated-wall or smooth-core corrugated plastic pipe of given inside diameter (Di) and assumed neutral-axis diameter (Dna), and which is made of a given plastic resin material of known modulus-of-elasticity (E), the only term unknown in the above formula is (I), which represents the pipe-wall moment-of-inertia. Corrugation shape and smooth interior wall features govern the magnitude of (I), the major structural parameter of the plastic pipe determined or controlled through product design and fabrication.

Pipe-Wall I-Value

In a previously published corrugation design procedure (Fouss, 1973), specific geometrical features of the corrugated-wall cross-sectional profile were represented in simplified forms or standard geometrical shapes (e.g., rectangular sections) to simplify the development of analysis equations for the I-value of the pipe-wall. The smooth-core corrugated pipe-wall profile shown in Fig. 1 is represented in simplified form as shown in Fig. 2 for the analysis procedure presented here. This simplification is similar to that presented earlier by Fouss (1973), but the corrugation "root" is represented with a 'semi-circular' area, which is more typical of the pipe-wall profiles used for current pipe products. No attempt has been made for this paper to consider the more complex profile features, such as curved sections or fillets, the angle of the corrugation web, wall thickness variations within each corrugation section, etc. Analysis procedures for complex pipe-wall profiles have been developed and are in use by industry, but the development of such equations for the profile in Fig. 1 was beyond the scope of this paper.

A set of formulas was derived to compute the moment-of-inertia (I) of the simplified smooth-core corrugation profile below on a per corrugation pitch (P) basis, and per unit length (mm) of pipe. The classical principles of engineering mechanics were applied for these derivations. Published formulas for computing the (Ix-x) for standarized shapes or sections (such as rectangles or circular arcs) about their own neutral-axes (x-x) were

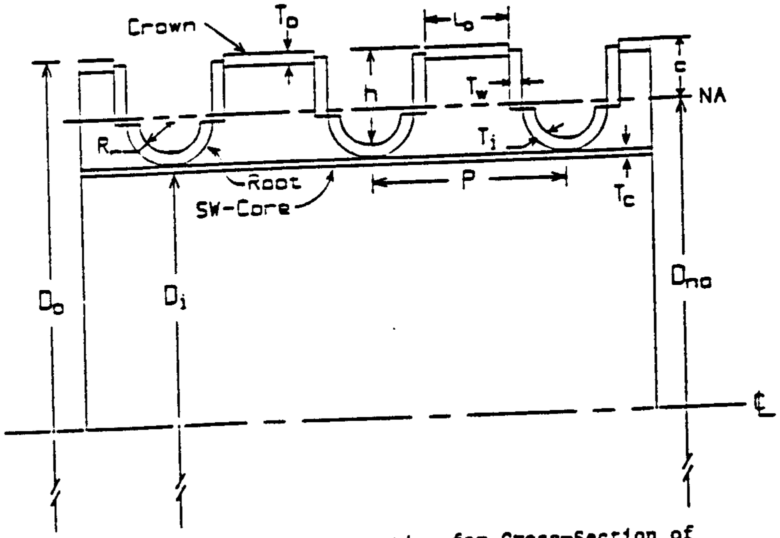

Fig. 2 Simplified Representation for Cross-Section of Smooth-Core Corrugated Profile for Analysis.

used, then the (Ix-x) values were "transferred" to the neutral-axis (NA) of the complete smooth-core corrugated pipe-wall profile (Fig. 2) by the "rule", [(section-area) x (square of the distance between x-x and NA)]. Thus, the I-value for the complete pipe-wall profile about the NA of the pipe-wall became the summation of a series of composite values for the various geometric shapes in the profile. The derived formulas to compute the I-value-component for the various area shapes to represent the total pipe-wall profile (Fig. 2) are given below. The formulas were not reduced to their simpliest form, but rather the first terms represent the (Ix-x) for the shape about its own neutral-axis, and the remaining terms are for the "transfer" of the Ix-x value to the pipe-wall NA. A formula to compute the distance "c" (for the position of the pipe-wall NA) is not shown; "c" can be determined by the summation of area-moments method (reference an engineering mechanics text).

The following formulas were derived to compute the I-values of the component areas of the simplified profile (Fig. 2), per corrugation pitch (P):

$$I\text{-crown} = \frac{Lo\ (To)^{3}}{12} + Lo\ To\ [c - (To/2)]^{2}$$

$$I\text{-web} = \frac{2\ Tw\ [h - (To/2) - Rr]^{3}}{12} + 2\ Tw\ [h - (To/2) - Rr] * \{c - To/2 - [h - (To/2) - Rr]/2\}^{2}$$

$$I\text{-root} = \frac{\pi}{8}\ [(Rr + Ti)^{2} - (Rr)^{2}]^{2} + \frac{\pi}{2}\ [(Rr + Ti)^{2} - (Rr)^{2}] * (h - Rr - c)^{2}$$

$$I\text{-core} = \frac{P\ (Tc)^{3}}{12} + (P\ Tc) * [h + Ti + (Tc/2) - c]^{2}$$

The I-value per unit length of pipe was given by summation of the parts,

I = (I-crown + I-web + I-root + I-core) / P , in (mm^{4}/mm).

For regular corrugated-wall pipe, the I-core term would not be used to compute the I-value for the pipe-wall profile. For regular smooth-wall pipe, $I = [(Tw)^{3}]/12$, where Tw = pipe-wall thickness.

HYDRAULIC EQUIVALENCE OF CIRCULAR PIPE

From fluid mechanics the basic equation for computing the hydraulic "full" flow capacity of circular cross-section pipes is:

$$Q = [\ 1.49 * A * R^{(2/3)} / n\ ] * s^{(1/2)} ,$$

where,

Q = flow capacity or rate, m^{3}/sec
A = cross-sectional area of pipe, m^{2}
R = hydraulic radius of pipe, m
  R = A/p, where p = wetted perimeter, m
  or, p = π * Di < π = 3.1416>
  Di = pipe inside diameter, m
  [for circular pipe R = Di/4]
n = Manning's hydraulic roughness coefficient (dimensionless)
s = hydraulic gradient of pipe, m/m
1.49 = proportionally constant, 1/sec

A coefficient 'F' was defined from the above equation that is proportional to the relative "full flow" capacity of pipes installed at the same grade. For conditions when the hydraulic gradeline (gradient, s) is parallel to the bottom grade of the pipe, and the pipe flows full without back pressure, the flow capacity (Q) will be EQUAL to that of other pipes with the same value of 'F', defined as:

$$'F' = [\ 1.49 * A * R^{(2/3)} / n\ ]\ ,\quad \text{with units of } (m^3/sec).$$

This 'F' value was used to compare relative full flow capacity of smooth-core corrugated PE, corrugated-wall PE, corrugated galvanized steel, and smooth-wall plastic and concrete pipes for various diameters, as presented herein.

STRENGTH-TO-WEIGHT RATIO

The strength-to-weight ratio was used as an indication of plastic-use-efficiency for smooth-core corrugated vs. corrugated-wall vs. regular smooth-wall PE pipes of "example" designs. The parallel-plate strength (load carrying capacity) at a pipe deflection of 5% of Di was used. That is, the parallel-plate load carrying capacity (@ 5% deflecton) per unit of plastic material weight in the pipe wall, as defined below:

$$\text{Strength/weight} = \frac{(W/\Delta Y)}{w} * 0.05 * Di\ ,\quad \text{(kg-strength/kg-weight), or (kg/kg).}$$

where,

w = pipe weight, kg/mm length.

Analyses were conducted for example smooth-core corrugated and corrugated-wall PE pipes with "selected" physical and material characteristics which provided some hypothetical design consistency between pipes of the various diameters. For regular corrugated-wall pipes with diameters from 203 to 914 mm, principal corrugation profile dimensions were determined by the following equations for the example pipes:***

$$h = 0.085 * Di\ ,\qquad P = 0.153 * Di, \text{ for } 203 \text{ mm} \leq Di \leq 457 \text{ mm};$$

$$\text{and}\qquad P = 1.0 + 0.097 * Di\ , \text{ for } Di > 457 \text{ mm}.$$

Analyses were conducted for smooth-core corrugated pipes with the h and P values also determined with these equations. An additional design option for the smooth-core corrugated pipe was analyzed, where the h-dimension was increased by 20%; i.e., $h = 1.2 * 0.085 * Di$.

The structural analyses were conducted for a required pipe stiffness value of $(W/\Delta Y) = 3.234 \times 10^{-2}$ kg/mm^2 (46 psi), which meets the strength requirements for corrugated plastic pipe as specified in ASTM D-3034 and AASHTO M252. A high-density polyethylene (HDPE) plastic resin was assumed to have a modulus of elasticity (E) of 63.3 kg/mm^2 (90,000 psi), and a specific gravity (p) of 0.954. For the smooth-core corrugated pipe analyses, a plastic material distribution ratio in the pipe-wall was assumed as, (%corrugated / %smooth) = (65%/35%).

*** NOTE: Numerical examples used in the paper to illustrate strength-to-weight relationships are hypothetical, for reader informational purposes only; plastic material strength characteristics were assumed and do not represent a commonly used HDPE resin. The examples DO NOT knowingly describe any pipe now on the market or planned for production by any particular manufacturer. The equations used to estimate h and P for the example pipes are not intended as design guidelines; pipe on the market would indicate that these relationships, if they exist, are non-linear with diameter.

A personal computer (PC) program was developed (not included here) to solve the above equations for (I) and (W/ΔY) in an iterative method to determine the minimum pipe-wall thickness to meet the pipe stiffness requirement. The PC program also estimated the pipe weight and computed the strength/weight ratio. The results of these structural analyses are summarized graphically in Fig. 3, where the strength/weight (str/wt) ratio is plotted as a function of pipe diameter for example smooth-core corrugated, corrugated-wall and smooth-wall PE pipes. The smooth-core corrugated profile with the same depth of corrugation (h) as that for the corrugated-wall pipe increased the strength/weight ratio by 23 to 34% over that for the corrugated-wall profile. For the smooth-core corrugated profile with corrugation depth (h+) increased by 20%, the strength/weight ratio was 21 to 29% higher than that for the smooth-core corrugated profile with the previous (smaller) h-value, and 58 to 68% higher than that for the regular corrugated-wall profile with the smaller h.

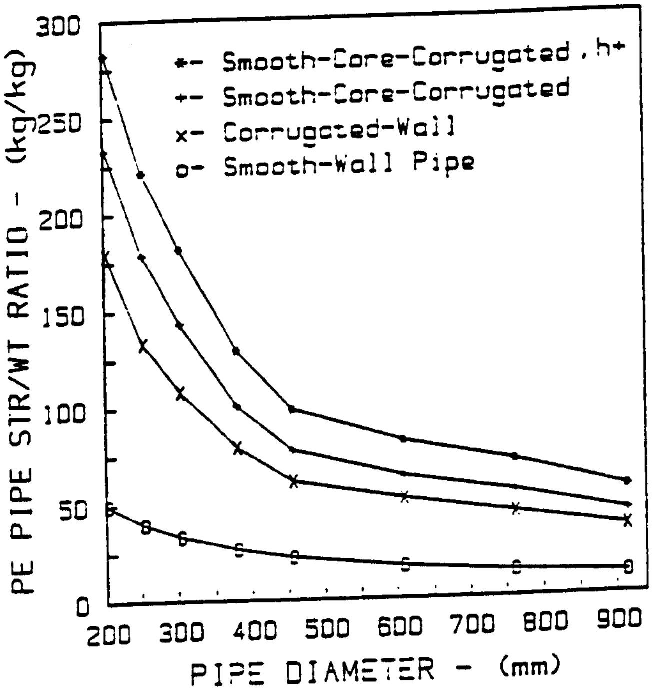

Fig. 3 Strength/Weight Ratio vs. Diameter for Smooth-Core Corrugated, Corrugated-Wall, and Smooth-Wall HDPE "Example" Pipes; Pipe Stiffness Constant at 3.234×10^{-2} kg/mm^{2} (46 psi).

RELATIVE PIPE WEIGHT

The weight of a pipe per unit length is an important parameter in evaluating its handling and transport characteristics. A "relative pipe weight" parameter was used so that various piping materials could be compared. The weight of the "example" 203-mm (8-in.) diameter smooth-core corrugated, with standard corrugation depth (h), was assumed equal to "<u>1.0</u>". The unit weights of all other example pipes used in the analyses were divided by the estimated weight of this pipe, thus computing a relative pipe weight for each. The results of this evaluation are presented graphically in Fig. 4; the reader should note that the ordinate for the concrete pipe is on the right-hand side of the graph. The lightest pipes were the smooth-core

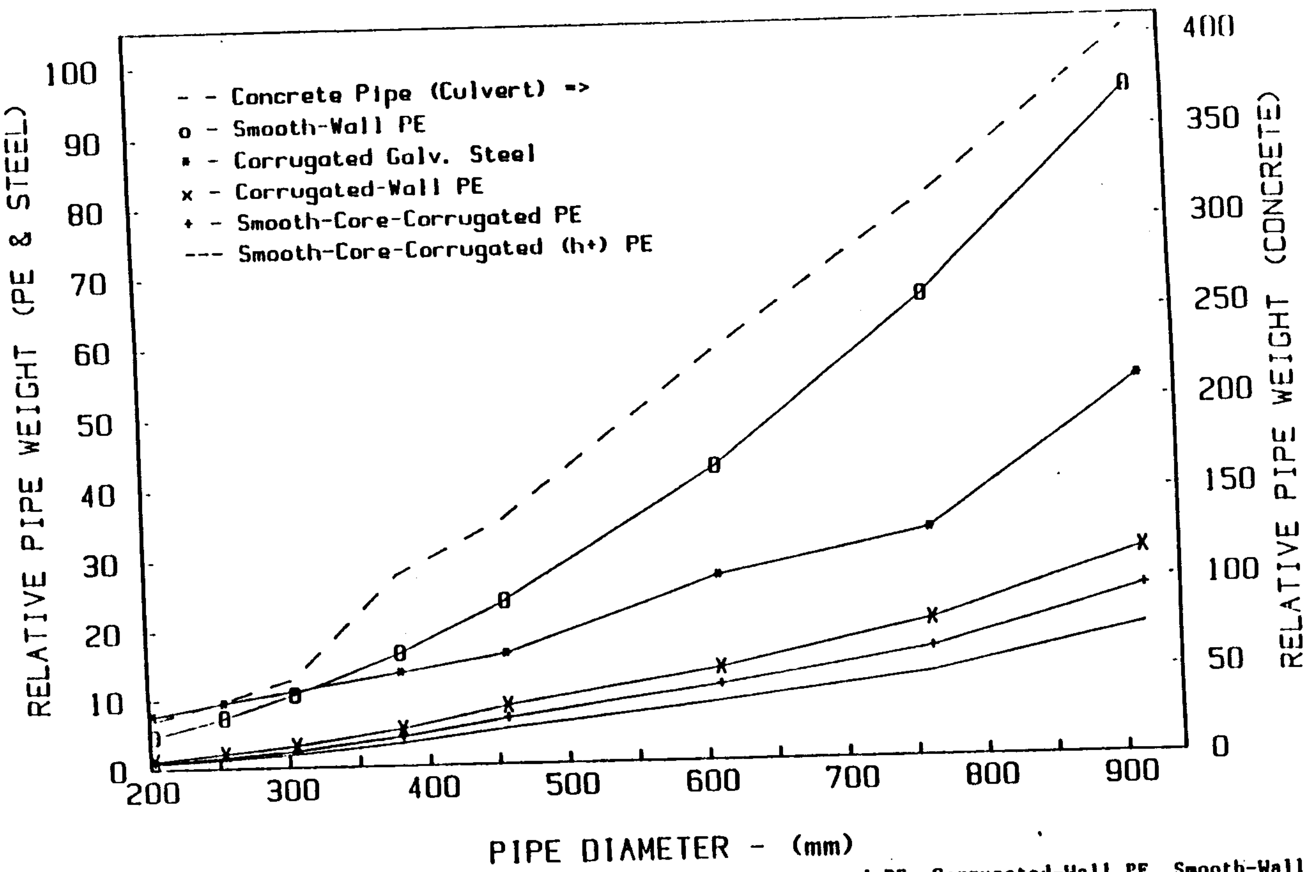

Fig. 4. Relative Pipe Weight vs. Diameter for Smooth-Core Corrugated PE, Corrugated-Wall PE, Smooth-Wall PE, Corrugated Galvanized Steel, and Concrete Pipe (Note: Ordinate for Concrete is on the right.) [Assumed: Weight of 203 mm Dia. Smooth-Core Corrugated = 1.0]

corrugated and corrugted-wall PE, which ranged from 13 to 45% less relative weight than the corrugated galvanized steel pipe; the greatest weight reductions were estimated for the larger diameters. The estimated relative weight for smooth-wall .PE pipe was significantly greater than that for the example PE corrugated pipes, and was also much greater than that for corrugated steel at diameters larger than 457 mm (18 in.), see Fig. 4. The concrete culvert pipe (Class I), assumed reinforced with steel for diameters larger than 305 mm (12 in.), was approximately 4 times heavier than the smooth-wall PE pipe, and ranged between 16 and 27 times heavier than the corrugated PE pipes (largest difference at the smaller diameters).

RELATIVE HYDRAULIC CAPACITY

The various values of Manning's hydraulic roughness coefficient, n, used for the different pipe materials, diameters, and pipe-wall configurations are given in the Table 1. The value of "n" = 0.012 for the smooth-core corrugated pipe was within the range, 0.011 to 0.014, typically used for concrete pipe (CE Handbook, 1982; ASAE SW-232). The relative flow coefficient 'F' was computed for each of the pipe material, diameter, and n-value combinations (Table 1), and the results are summarized graphically in Fig. 5. The full flow capacity of the smooth-core corrugated pipe was nearly equal to that for smooth-wall PE or concrete pipe. The regular corrugated-wall PE pipe flow capacity was slightly greater than that for corrugated galvanized steel pipe for all diameters (203 to 914 mm). The increase of flow capacity for the smooth-core corrugated pipe over that for the corrugated-wall pipe varied from 24 to 83%; the flow capacity was proportionally greater for the larger diameter pipes because of the higher n-values. For the popular 457 and 610 mm (18 and 24 in.) diameter pipes, the flow capacity for the smooth-core corrugated pipe was estimated as 67% greater. For the "example" pipes shown in Fig. 5, a 381-mm (15-in.) diameter smooth-core corrugated pipe is equivalent in flow capacity to a corrugated-wall pipe of 457-mm (18-in.) diameter. Similarly, a 610-mm (24-in.) diameter smooth-core corrugated pipe is equivalent to a 762-mm (30-in.) diameter corrugated-wall pipe, and finally a 762-mm smooth-core corrugated pipe exceeds the capacity of a 914-mm (36-in.) corrugated-wall pipe.

Table 1. MANNNING'S ROUGHNESS COEFFICIENT, n, FOR CIRCULAR PIPES OF VARIOUS MATERIALS AND DESIGNS; DIAMETERS from 203 TO 914 mm.

Pipe-Wall Cross-Sect. Design	Pipe Diameter(s), Di (mm)	(in.)	Manning's Hydraulic Roughness Coefficient (n)	Source for "n" Value
Regular Smooth-Wall PE or Concrete *	203 to 914	(8) to (36)	0.011	CE Handbook
Smooth-Core Corrugated PE Pipe	203 to 914	(8) to (36)	0.012	Est. from: ASAE SW-232 & CE Handbook
Corrugated-Wall PE Pipe	203	(8)	0.015	ASAE SW-232
	254, 305	(10, 12)	0.017	ASAE SW-232
	381	(15)	0.018	<estimated>
	457, 610	(18, 24)	0.020	ASAE SW-232
	762, 914	(30, 36)	0.022	<estimated>
Corrugated Galvanized Steel Pipe	203 to 914	(8) to (36)	0.024	CE Handbook

* For concrete pipe with "well" aligned joints.

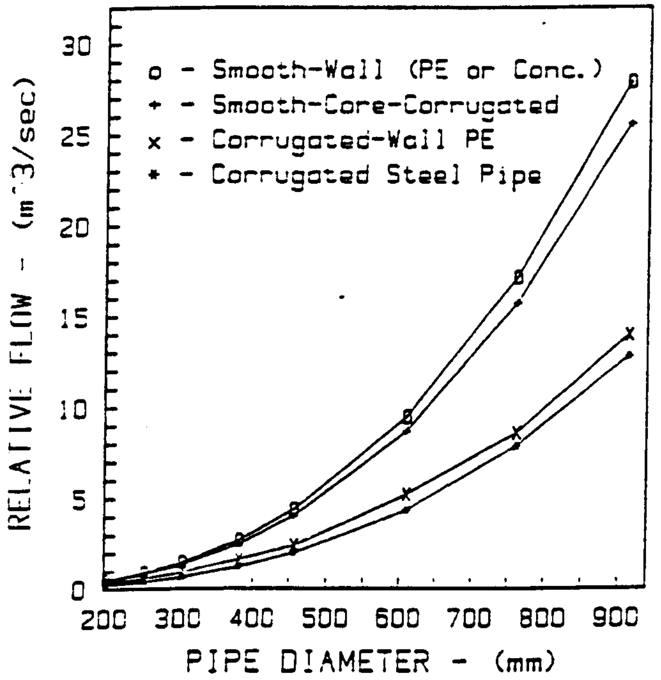

Fig. 5 Estimated Relative Flow Capacity of Various Circular Drainage and Culvert Pipes, 203 to 914 mm in Diameter.

SUMMARY COMMENTS

The structural and hydraulic characteristics of smooth-core corrugated and corrugated-wall PE pipes were analyzed and compared analytically. The smooth-core corrugated pipe-wall configuration significantly increased the efficiency-of-use of plastic material in the pipe wall to support the design load in contrast to the regular corrugated-wall pipe. Plastic use efficiency was expressed as the (strength-to-weight) ratio of the pipe structure. The smooth-core corrugated design increased the pipe's strength/weight ratio from 23 to 34% over that for the corrugated-wall design when both had the same depth of corrugation (h). When the corrugation depth for the smooth-core corrugated profile was designed 20% greater, the increase in the strength/weight ratio was even larger, at 58 to 68%. Thus, the combination of the smooth-wall core and a 10 to 20% deeper corrugation significantly increased the stength/weight ratio (plastic-use-efficiency) for the smooth-core corrugated pipe over that obtained for the comparable corrugated-wall design.

Both types of corrugated PE pipes have a significant advantage over other pipe products in terms of relative weight per unit length of pipe and ease of handling light-weight pipe sections. The relative pipe weights of smooth-core corrugated and corrugated-wall PE example pipes were estimated as 13 to 45% less than that for corrugated steel pipe, an average of 75% less than the unit weight of smooth-wall PE pipe, and 16 to 27 times less than that for concrete culvert pipe.

The full flow capacity of the smooth-core corrugated pipes was from 24 to 83% greater than that for regular corrugated-wall pipes, with the greatest differences for the larger pipe diameters because of the higher n-values. The estimated higher flow capacity for the smooth-core corrugated pipes indicated the following "equivalent" pipe diameters: a 381-mm (15-in.) smooth-core corrugated pipe was equivalent in flow capacity to a 457-mm (18-in.) corrugated-wall pipe, a 610-mm (24-in.) smooth-core corrugated equivalent to a 762-mm (30-in.) corrugated-wall, and a 762-mm smooth-core corrugated exceeded the capacity of a 914-mm (36-in.) corrugated-wall pipe. Thus, the pipe diameter requirements or specifications as stated in some standards may need to be revised, to reflect these large differences in flow capacities for corrugated-wall and smooth-core corrugated pipes of the same diameter.

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