Tensile strength of the pipe material determination according to the ultimate tensile strength

B Younis\textsuperscript{1}, L Saienko\textsuperscript{2}, I Kazimahomedov\textsuperscript{3} and S Salem\textsuperscript{3}

\textsuperscript{1}Department structural Mechanics, Kharkiv National University of Civil Engineering and Architecture, Sumska Street 40, 61000, Kharkiv, Ukraine
\textsuperscript{2}Department of Mechanization of Construction Processes, Kharkiv National University of Civil Engineering and Architecture, Sumska Street 40, 61000, Kharkiv, Ukraine
\textsuperscript{3}Department of building Materials and Products, Kharkiv National University of Civil Engineering and Architecture, Sumska Street 40, 61000, Kharkiv, Ukraine

sesonoor@yahoo.com

Abstract. A new calculation method for the strength of concrete pipes, developed, helps to determine the stresses in the walls of concrete pipes under the combined action of an external (compressing pipe) load and internal pressure from the fluid transported under pressure. An analysis of the nature and magnitude of the stresses is necessary to choose the material of the pipe walls, as well as to establish a possible combination of ultimate external. New formulas make it possible to determine the stresses in the pipe walls under the combined action of an external load and internal pressure. Based on the developed formulas, it was found that the main dangerous stresses in the pipes are tensile stresses. Using the obtained equations allows to determine the range of application of pipes made of modified concrete and to select the necessary concrete strength based on operational loads.

There are two methods for determining the bearing capacity of pipeline: three-edge bearing method, in which the maximum breaking load (ultimate), and hydro-static loading method to determine the maximum internal pressure.

The design of the test bench for pipes was developed in order to determine the maximum internal pressure on the pipe walls.

1. Introduction

The modern requirements to the quality of construction products are not inferior to the demands for the newest architectural elements \cite{1-4}. In addition to the high requirements for physico-mechanical characteristics and durability of concrete and reinforced concrete pipes, the requirements for the quality and casting techniques are set.

In today’s economic environment, designing for long term, sustainable project performance is imperative for the Engineer. Unlike some alternate pipe materials, concrete pipe has a proven track record of performance. Concrete pipe will not rust, burn, tear, buckle or deflect, and is immune to most environmental elements. Corps of Engineers has recommended precast concrete pipe for a design life of 70-100 years, and there are numerous examples of installations that have exceeded these parameters. Precast concrete drainage products have a reputation for strength and durability. They will not burn, corrode prematurely, deflect or move off grade to reduce hydraulic performance, or collapse under loads designed into the pipe structure. Comprised of the world’s most commonly used building materials, precast concrete infrastructure is quickly integrated into ecosystems. This is clearly demonstrated by the
use of three-sided precast boxes used to accommodate the natural channels of streams at road crossings, and precast concrete pipe for storm sewers and outfalls in valleys and shorelines.

Today, being recognized as a green material or product is growing in importance to many specifiers. Concrete pipe is suitable for LEED projects and it fits sustainable development.

Unlike plastic pipe, concrete is produced with benign, natural materials. Manufacturing of concrete consumes less energy than plastic fabrication. It’s also recyclable and has little if any environmental impact. And, when you use local resources, concrete can also provide lower fuel cost for delivery [5, 6].

Reinforced concrete pipes have been in wide-spread use for many decades in the world. They have often been used as open channels (non-pressurized pipes), particularly for the conveyance of sewage and storm water. They have generally shown reliable long-term performance. In the late 1890’s, the manufacturing of precast concrete pipes became a recognizable industry in Ontario. The Ontario Concrete Pipe Association (OCPA) was founded in 1957. OCPA has joined several industrial and governmental agencies to establish standards for the manufacture of high quality concrete pipe products. The Canadian Concrete Pipe Association (CCPA) was founded in 1992 (OCPA, 2010). Reinforced concrete (RC) pipes are widely used as open channels (non-pressurized pipes) for sewage and storm water conveyance. RC pipes have generally achieved a reliable long-term performance. Depending on multiple parameters (e.g. pipe diameter, pipe wall thickness, required strength, etc.) the pipe may have up to three welded reinforcement cages in order to resist anticipated loads. Each cage is an assembled unit of steel reinforcement consisting of circumferential and longitudinal bars or wires. The fabrication process of steel cage reinforcement is time- and labour-consuming. Thus, eliminating the steel cage reinforcement will yield an overall reduction in the production cost of precast concrete pipes [5, 7].

Purpose of the work – to determine the stresses in the walls of concrete pipes under the combined action of an external (compressing pipe) load (see formula №5), and internal pressure from the fluid transported under pressure (see formula №6). An analysis of the nature and magnitude of the stresses is necessary to select the material of the pipe walls, as well as to establish a possible combination of the maximum external loads (the pipeline depth – the magnitude of the working fluid pressure). These formulas are not identical in terms of initial data: in the Lyame formula, the dependence is taken according to the inner and outer diameters.

In the Klein formula [3, 8], the average diameter of the pipe is adopted. Wall thickness is not taken into account. It turned out to be impossible to select the wall thickness under the combined action of internal pressure and external soil load, so we modified the formulas. A new indicator has been introduced: the ratio of diameter to wall thickness, which, when switching from one diameter to another for pipes, retains its average values with some deviations. The new formulas developed allow to determine the stresses in the walls of pipes under the combined action of external load and internal pressure. The formulas showed that the main stresses in the pipe walls are tensile stresses. It follows from this that the guidelines given in the standards for concrete strength in the form of a concrete grade for compressive strength do not correspond to the actual work of the material in the product. Based on the regulatory requirements for reinforced concrete pipes (breaking load) according to the developed formulas, the necessary material strength was calculated \( R_{m1} \), which, depending on the magnitude of the working pressure, should be in the range of 50-70 kg/cm\(^2\). As for ordinary concrete tensile strength \( R_{t0} = 1 \ldots 4 \) MPa, the problem arises of increasing this indicator by modifying concrete.

2. Experimental

There are two methods for determining the bearing capacity of pipeline:

1. Three-edge bearing method, in which the maximum breaking load (ultimate) \( P \) is established for 1 running meter of a pipe.

The structural load test, also known as the three-edge bearing test, is a destructive test that has been commonly adopted to evaluate the crack load and ultimate load of RCP. The test has over 100 years of history indicating its success in RCP assessment. This is a primary acceptance test among all study areas, though the examination process and interpretation of the test results are slightly different. In common, the testing procedure is to apply load evenly on a vertical plane along the pipe and the pipe axis. The
load definition and terminology vary among study areas and are translated for consistency in Figure 1 illustrates load progression during the three-edge bearing test and the critical load definitions. The load in most procedures is applied to the pipe either in continuous or discrete manner. The inspector examines the crack development by measuring the crack width and length using a crack gauge. Subsequently, the load is carried to the design crack load and in some study areas, the pipe is loaded to failure [9].

![Figure 1. Three-edge bearing test.](image)

2. Hydrostatic loading method to determine the maximum internal pressure \( q \). For testing concrete and reinforced concrete pipes with hydrostatic pressure, a setup is used, the diagram of which is shown in Figure 2.

![Figure 2. Scheme of a standard installation for hydrostatic testing of pipes: 1 – concrete pipe; 2 – end plug 3 – rubber sealing ring; \( V_o \) – test fluid volume.](image)

The test is carried out as follows: two pipes (1) horizontally mounted on the bench are filled with water. At the ends, plugs (2) with rubber O-rings (3) are installed. When creating hydrostatic pressure inside, water exerts a lot of pressure on the end caps. The pressure of the rubber rings (their compression) should be such that the pressure of the rubber on the concrete is always (during the tests) greater than the maximum test pressure, i.e. at the place of installation of the seals, their pressure on concrete is greater than the test pressure \( q_{\text{te}} \), which distorts the test results.

To increase the reliability of indicators and greater convenience of testing, a new method and device for testing was developed.

Figure 3 shows the studied pipes subjected to hydrostatic pressure test.

The proposed test procedure has the following advantages over those already known:

– less water used in the pipes,
– automatic maintenance of the pressure of the elastic sealant on concrete, proportional to the value of the test pressure due to the fact that the pressure in the sealing annular chamber is 20% higher than inside the pipe (test pressure), which eliminates the overload of concrete.

This is especially important for unreinforced concrete pipes.
Figure 3. The developed scheme of hydrostatic testing of pipes:
1 – concrete pipe; 2 – ring sealing chamber; 3 – working cavity; 4 – thrust ring; 5 – input test fluid; 6 – introduction of fluid into the annular chamber; $V_n$ – volume of the test fluid.

Improved methods and devices are a new solution compared to the known ones, where concrete mixture impregnation can be used.

The design of the test bench for pipes was developed in order to determine the maximum internal pressure on the pipe walls (Figure 4).

Figure 4. Installation diagram for hydrostatic testing of pipes with automated backpressure in the sealing ring:
1 – tested pipe; 2 – annular chambers; 3 – working cylinder; 4 – working piston; 5 and 6 – pressure conversion cylinders; 7 – piston under operating pressure $q_T$; 8 – piston transmitting back pressure $q_G$ in the annular hose; 9 – pressure gauge.

The stand has a steel cylinder placed inside the test pipe (1), sealing elements in the form of elastic annular chambers (2) installed at both ends in the space between the cylinder and the pipe (1), a device in the form of twin cylinders (5), (6) with pistons (7) and (8). A test pressure is applied to the piston 7, $q_T$ which under the piston 8 is converted into a back pressure $q_G$. The pressure in the system is controlled by a manometer (9).

Ealing pipes with a known method of testing internal pressure (Figure 5). So that water does not flow out through the sealing ring, the pressure of the ring $P$ should be 1.25 greater than the test pressure $q$; $P \geq 1.25 q$. 

Since the value of the limiting pressure \( (q_{max}) \) is not known, during testing it is necessary to significantly compress the ring \( (P \geq q) \), due to which the pressure of the ring \( P \) creates accordingly an excessive force in concrete and, therefore, distorts the test results. In Japan, to reduce the pressure of the sealant, an additional device with a separate pump is used, which creates electronics back pressure, presses the ring with force, which accordingly maintains the level of \( P = 1.25q \).

In the developed stand, a device with two pistons of different diameters is used for this. Due to the difference in diameters, a different pressure is created under each piston, and by selecting their diameters, the pressure inside the ring is \( P = 1.25q \).

Calculation of operating parameters of the converter device (Figure 6) The task of research is to obtain pressure in the sealing chamber \( (1) \) \( q_G \), exceeding the test pressure \( q_T \) by "n" times, i.e. \( q_G = nq_T \).

In the piston connecting rod 2 \( (d_1) \) and 3 \( (d_2) \) a force \( F \) arises, which is equal to "0" under equilibrium conditions, when the total pressure on the area \( S \) of the pistons on each side is balanced i.e \( \sum q_1 = \sum q_T \), then in equilibrium:

\[
F = q_m \cdot S_1 = q_G \cdot S_2,
\]

\[
S = \frac{\pi d^2}{4}. \tag{2}
\]

The increase in pressure in the ring is achieved by reducing the diameter of the piston \( (d_2) \) compared to the piston \( (d_1) \):
\[ q_o = \frac{q_r \cdot S_1}{S_2} \]  

then

\[ q_o = \frac{q_r \cdot d_1^2}{d_2} \]

The pilot plant was made with the following dimensions of the pressure transducer: \( d_1 = 60 \) mm and \( d_2 = 54.5 \) mm, which gives the ratio \( q_o = 1.2 q_t \).

Normal stress determination (\( \sigma_p \) and \( \sigma_q \)) based on values \( P \) and \( q \) material strength using the obtained values \( P \) and \( q \). Use the formulas:

\[ \sigma_p = \frac{1.1 \cdot P \cdot r_{av}}{b \cdot c^2}, \]

where \( P \) – reduced loading, \( r_{av} \) – average pipe radius, \( c \) – wall thickness.

Under the action of internal pressure \( q \) (kg/cm\(^2\)) we have:

\[ \sigma_q = q \cdot \frac{r_H^2 + r_B^2}{r_H^2 - r_B^2}, \]

where \( q \) – internal pressure, kg/cm\(^2\), \( r_H \) and \( r_B \) – respectively the outer and inner radius of the pipe.

Due to the fact that formulas (5) and (6) show various geometric parameters that cannot be used in the design of pipes, the ratio \( n = \frac{d}{c} \) allows us to bring formulas (5) and (6) to the form:

\[ \sigma_p = A \cdot \frac{P}{d}, \text{ where } A = 0.0055n \cdot (n + 1), \]

\[ \sigma_p = q \cdot B, \text{ where } B = \left[ \frac{n^2}{2n + 2} + 1 \right] \]

The values of \( A \) and \( B \) are given in tabular form [3, 11]. Showed that for concrete and reinforced concrete pipe ratio \( \frac{d}{c} \) lies in a narrow range in which the table values \( A \) and \( B \) can be replaced by analytical expressions:

\[ A = 0.007618 \cdot n^{1.9} \]

\[ B = 0.78 \cdot n^{0.85} \]

In order to simplify the dependencies (9) and (10), additional studies were carried out that showed the possibility of using the coefficients \( A \) and \( B \) in a narrow range of actually used pipes (n = 6 .. 9). Which makes it possible to use the calculator in engineering calculations. In this range for external load (\( P \)):

\[ A = 0.0064 \cdot n^2 \]

\[ \sigma_p = 0.0064 \cdot n^2 \cdot \frac{P}{d} \]

For internal pressure:

\[ B = 0.491 \cdot n + 0.621 \]

\[ \sigma_q = q \cdot (0.491 \cdot n + 0.621) \]
3. Results

Table 1 shows the comparative results of calculations by the exact formulas (7), (8) and the proposed ones (11), (13). The calculated deviations do not exceed 2.4%.

| $n = \frac{d}{c}$ | $A = 0.055n \cdot (n+1)$ | $A = 0.0064 \cdot n^2$ | Deviation by A | Relative, % | $B = \left[ \frac{n^2}{2n+2} + 1 \right] + 0.621$ | Deviation by B | Relative, % |
|------------------|----------------|----------------|-------------|----------|----------------|-------------|----------|
| 6 | 0.230 | 0.230 | 0 | 0 | 3.571 | 3.567 | 0.006 | 0.10 |
| 7 | 0.308 | 0.313 | 0.005 | 1.6 | 4.062 | 4.058 | 0.011 | 0.09 |
| 8 | 0.396 | 0.409 | 0.010 | 2.5 | 4.555 | 4.459 | 0.012 | 0.13 |
| 9 | 0.495 | 0.518 | 0.020 | 2.4 | 5.050 | 5.04 | 0 | 0.19 |

Example 1: Determine the voltage limit $\sigma_p$ for a concrete pipe with an inner diameter of $d = 1000$ mm, wall thickness = 89.5 mm, ultimate test load $p = 5970$ kg/running metre. Pipes are made on the SIOME hyro press machine. Substitute the source data:

$$n = \frac{d}{c} = \frac{1000}{89.5} = 11.17$$

Using the formula (12), we have: $\sigma_p = 0.0064 \cdot 11.17^2 \cdot \frac{5970}{1000} = 4.7$ MPa.

Example 2: Determine the voltage limit $\sigma_q$ for a concrete pipe with an inner diameter of $d = 1000$ mm, wall thickness = 89.5 mm, if the test hydro-static pressure = 6.9 kg/cm². Pipes are made on the SIOME hyro press machine. Substitute the source data:

$$n = \frac{d}{c} = \frac{1000}{89.5} = 11.17$$

According to the formula (14): $\sigma_q = 6.9 \cdot (0.491 \cdot 11.17 + 0.621) = 42.15$ kg/cm² = 4.21 MPa.

Example 3: Determine the maximum pressure that a modified concrete pipe can withstand $R_{bt} = 72$ kg/cm², $d = 1000$ mm, wall thickness = 89.5 mm. Design tensile strength: $R_p = 0.6 \cdot R_{bt} = 0.6 \cdot 72 = 43.2$ kg/cm²

According to the formula (14):

$$q = \frac{43.2}{(0.491 \cdot 11.17 + 0.621)} = 7.07$$

The result shown in Example 3 showed that the use of modified concrete makes it possible to produce pipes for pressure pipelines.

Conclusion – conversion of known dependencies, allowing to determine the normal annular stresses from the external load $P$ and internal pressure $q$, allowed to obtain new transformed dependencies for calculating stresses in pipes under the combined action of internal pressure and external (reduced) load. Using the obtained equations allows you to determine the range of the application of pipes of modified concrete and to select the necessary indicator of its strength.
4. References

[1] Runova R F, Gotz V I and Sanytsky M A 2008 Design materials of the new generation and technology in the future

[2] Jamrozy Z 2000 Concrete and its technologies (Scientific publishing house Pwn., Warsaw)

[3] Shumakov I and Basheer Y 2014 International Journal of Engineering Science and Innovative Technology 3 6 562-567

[4] Nikiforov S N 1955 Theory of Elasticity and Plasticity (Stroyizdat, Moscow)

[5] Schladweiler J C 2018 The History of Sanitary Sewer

[6] Asid N J and Wardoyo W 2018 Head loss detection for irrigation pipe system in Poncokusumo Agropolitan, Malang In AIP Conference Proceedings 1977 (1) 050001

[7] Mohamed N (2015) Experimental and Numerical Study on Full-Scale Precast Steel Fibre-Reinforced Concrete Pipes

[8] Klein G K 1969 Calculation of underground pipelines (Moscow: Stroyizdat)

[9] Younis B, Kazimahomedov I, Salem S, Kostuk T and Dedenyova E 2018 Casting of concrete and reinforced concrete pipes by vibro-vacuum technique In MATEC Web of Conferences 230 03022

[10] Wong L S and Nehdi M L 2018 Critical Analysis of International Precast Concrete Pipe Standards Infrastructures 3 (3) 18

[11] Younis B and Saienko L 2019 Dependence of Lamé transformation for concrete pipeline design calculation In IOP Conference Series: Materials Science and Engineering 708 (1) 012116