Steel Tape-Armored Polyethylene Pipe for Gas Transmission (I) — Development of Pipe —

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ABSTRACT A flexible pipe for gas transmission with composite structure has been developed, which can be installed without joints for long distances along meandering open-cut routes or in underground conduits. The structure of this pipe is such that multiple stainless steel tapes are gap wrapped in spiral on a polyethylene pipe, whereby the steel tape thickness is optimized to make the pipe applicable to a wide pressure range from medium- to high-pressures, while maintaining flexibility by minimizing the pipe wall thickness. Moreover, earthquake resistance is one of its advantageous features. In this report, the design of the steel tape-armored polyethylene pipe in conformity to the Technical Standard for Gas Facilities of Japan is described, together with the results of various characteristic evaluation tests on the prototype pipes.

1. INTRODUCTION

Polyethylene pipe for gas transmission [1] has a great possibility of being widely used in quake-prone Japan, since the pipe is flexible and earthquake resistant. Taking advantage of its flexibility among others, the pipe can be transported in long continuous lengths wound on a small reel to be installed for long distances without joints. With respect to the applicable internal pressure, the use of the pipe had been limited to the low pressure range of 0.1 MPa for gas transmission, but the range was approved in 2003 to extend to the medium pressure range B of 0.3 MPa. Although steel pipe and cast iron pipe are generally used above that pressure range, the practical applications overseas raise the prospect of using polyethylene pipe in higher pressure ranges.

A simple pipe structure using polyethylene pipe only would require, it was thought, a considerable wall thickness to make the pipe highly pressure resistant, thus greatly impairing the flexibility of the pipe, i.e. one of its inherent advantages. Accordingly, we proceeded to develop a composite structure for medium- to high-pressure pipes for gas transmission that satisfy the various requirements including sufficient pressure resistance, while maintaining the desirable flexibility. The design concept of a steel tape-armored polyethylene pipe (hereinafter called STAPP), together with the structure of the prototype pipe, will be presented in this report. Also presented will be the contents and the results of various characteristic evaluation tests using the prototype pipe that have been carried out in conformity to the Technical Standard for Gas Facilities of Japan.

The development of the mechanical fitting, an important technological element constituting the pipe system, will be reported in another paper [2].

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2. DESIGN OF STAPP FOR GAS TRANSMISSION

2.1 Pressure Range Applicable to Polyethylene Pipe

Table 1 shows the pressure range applicable to polyethylene pipes for gas transmission.

Table 1 Pressure range applicable to PE pipes for gas transmission.

Internal pressure (MPa)	~0.1	0.1~0.3	0.3~0.7	0.7~1.0	1.0~
Japan	Applicable	To be applicable			
Overseas	Applicable			To be applicable	

Whereas the applicable pressure range is limited to 0.3 MPa (medium-range B) domestically, it has been actually expanded to 0.7 MPa in overseas countries including UK and Germany. An appropriate increase of the wall thickness, which is necessary to make the pipe applicable to higher internal pressures, would present significant drawbacks in terms of flexibility and ease of long distance installation. Possibilities of reviewing the safety factor to expand the applicable pressures while suppressing the pipe wall thickness are currently being studied overseas, but such measures seems to be not very successful, given the higher pressures probably needed in future.

ISO 4437 (Buried PE Pipes for the Supply of Gaseous Fuels) specifies that the safety factor for designing polyethylene pipe wall thickness should be 2.0 or more, so that overall safety factors of around 3.0 are actually adopted in designing the polyethylene pipes that are used in pressure ranges of not more than 0.7 MPa. If we design a polyethylene pipe with an inside diameter of 150 mm and an internal pressure of 1 MPa using a safety factor of 3.0 in accordance with ISO 4437, the pipe would be required to have a wall thickness of as much as 22 mm. Such a thick-walled pipe would greatly degrade the flexibility making reel winding difficult, resulting in the necessity of jointing a number of short straight pipes in constructing gas transmission lines, and thereby loses the advantage of using polyethylene pipe.

2.2 Structure and Design of STAPP

The STAPP developed here has, as shown in Figure 1, a composite structure consisting of, from the inside: inner pipe of polyethylene, steel tape wrapping layer and plastic jacket. The steel tapes of stainless steel are wrapped in spiral with a constant gap in the pipe axis direction forming two layers, and two cloth tape layers are provided above and underneath the steel tape layers to serve as binding and bedding, respectively.

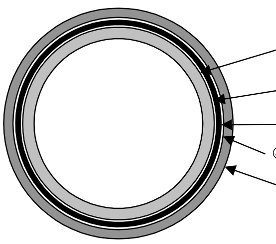

Figure 1 Cross section of STAPP.

Since no general standard for STAPP exists currently, it was decided that the design should be carried out adopting the Interpretation Examples of the Technical Standard for Gas Facilities of Japan [3] (hereinafter called Interpretation Example) as the most important guidelines, whereby the fundamental idea for designing the internal pressure resistance was defined as:

1) The thickness of steel tape should be such that the steel tape can bear the internal pressure, taking the safety factor into consideration.
2) The thickness of polyethylene pipe should be such that pipe alone can bear the internal pressure.

2.2.1. Steel Tape Thickness

The thickness of the steel tape was calculated using Equation (1), which has been applied conventionally to the design of steel tape reinforcement for water pipes and oil pipes, and subsequently the adaptability of the equation was reconfirmed by experiments as described later in Section 3.1. The numerical values used in the equation such as the internal pressure P and the allowable stress of steel tape σ have been appropriately selected based on the Interpretation Examples.

$$t = \frac{1.5PD}{(2\sigma \cdot F_f \cdot \sin^2\phi + P)} \tag{1}$$

where: D is the outside diameter of the polyethylene pipe, F_f is the reinforcement efficiency of the steel tape, and ϕ is the steel tape wrapping angle.

2.2.2. Polyethylene Pipe Wall Thickness

The wall thickness of the polyethylene pipe was calculated using Equation (2) in accordance with ISO and JIS.

$$MOP = \frac{2 \times MRS}{c \times (SDR - 1)} \tag{2}$$

where: MOP is the maximum operating pressure, MRS is the minimum required strength of polyethylene, c is the overall safety factor, and SDR is the ratio of outside diameter/wall thickness.

With respect to the wall thickness of the polyethylene pipe, it was decided to ensure a safety factor of not less than 1.0, whereby the pipe was expected to perform its function properly even in case of possible destruction of the steel reinforcement due to external damage. Based on the stipulated value in ISO 13761 and the results of long-term creep test using an all-polyethylene pipe, we settled on a safety factor of 1.4.

Table 2 shows the structure of a prototype pipe manufactured by way of trial for performance evaluation tests.

Table 2 Structure of prototyped STAPP.

Main layers (Material)	Function	Allowable stress (MPa)	Specification
Polyethylene pipe (PE 100)	Air-tight sealing of inner fluid	10	Inside diameter: 156 mm Wall thickness: 12 mm
Reinforcement layer for internal pressure (SUS 304 steel tape)	Reinforcement for internal pressure	232	0.35 mmt x 2
Outer sheath (polyvinyl chloride)	Protection against external damage		Thickness: 5 mm Outside diameter: 195 mm
Weight in air			12 kg/m

3. CAHARACTERISTICS OF STAPP

Various characteristics evaluation tests were carried out using the prototype pipe [4].

3.1 Stress in Steel Tape due to Internal Pressure

It is thought that when internal pressure acts on the STAPP, the pressure transmits to the steel tape through the polyethylene pipe, so that the most part of the pressure is borne by the steel tape. To confirm this, the strain in the steel tape due to the internal pressure was measured, and thereby the stress in the steel tape was analyzed.

3.1.1. Sample and Test Procedure

Both ends of a 3-m sample of STAPP were sealed using two flanges, and the flanges were connected by axial force reinforcements to make the sample free of the axial force that is caused by the internal pressure. See Figure 2.

The plastic jacket was removed at two locations separated in the axial direction to expose the steel tape, and strain gages were attached parallel to the tape axis, on each of the outer and inner layers of the steel tape, on four locations equally separated circumferentially. For the inner steel tape, small-sized strain gages were attached to the exposed areas between the windings of the outer steel tape.

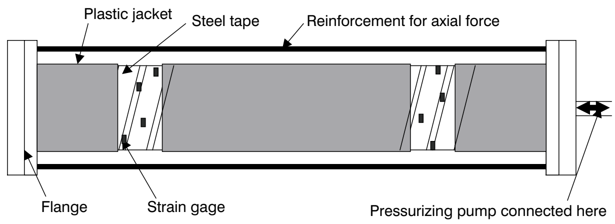

Figure 2 Sample for internal pressure test.

In the test five cycles of pressurization, depressurization and hold were applied, and during each cycle the changes in the strain in the steel tape were measured in 0.1-MPa steps up to the maximum pressure of 3 MPa, thereby the stress corresponding to these strain changes were calculated.

3.1.2. Test Results

Figure 3 shows the relationship between the internal pressure and steel tape stress measured in the fifth pressurization cycle, where the stress hysteresis over pressurization and depressurization became stabilized.

Calculation of the steel tape stress σ was done using Equation (3) which represents the hoop stress of a thin-walled circular cylinder.

$$\sigma = PD / 2t \cdot F_p \cdot \sin^2\phi \quad (3)$$

where: P is the internal pressure, D is the outside diameter, t is the thickness, F_p is the cross-sectional packing factor, and ϕ is the steel tape wrapping angle.

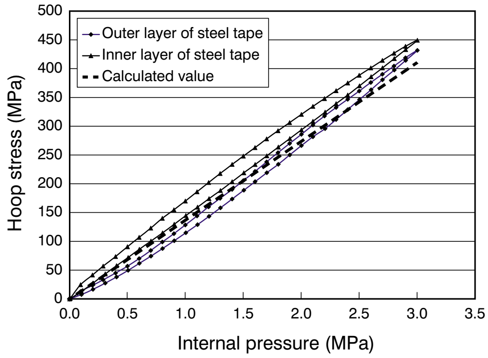

Figure 3 Relationship between internal pressure and steel tape stress.

The results show that, as can be clearly seen from the Figure, the measured steel tape stress is in good agreement with the calculated value, thus confirming that the internal pressure is almost entirely borne by the steel tape.

3.2 Internal Pressure Burst Characteristics

3.2.1. Test Method

In order to confirm the internal pressure burst strength of STAPP, the test sample was filled with water and was pressurized until burst.

3.2.2. Test Results

The internal pressure burst strength was measured to be 9.6 MPa, twice as high as the designed minimum burst strength of 4 MPa. The designed strength, having been set to four times or more the working pressure (i.e. 1 MPa), was calculated based on an allowable stress of steel tape that is one fourth the minimum tensile strength of steel material. Thus, the measured strength confirms that the design requirement is met, and that the actual pipe strength has been upgraded due to the margin in strength of the steel material actually used over the specified minimum value.

Meanwhile, the two stainless steel tapes completely broke at the burst portion, while the polyethylene pipe showed only swells without having breakage openings.

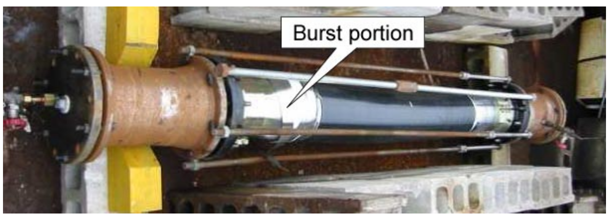

Photo 1 Internal pressure burst test.

3.3 Bending Characteristics

Bending deformation test was carried out to verify the flexibility of the STAPP.

3.3.1. Sample and Test Procedure

Two types of samples were used, i.e. a 3-m piece of STAPP and its inner pipe of polyethylene. As shown in Figure 4 and Photo 2, bending load was applied on the sample and the relationship between the bending angle and bending moment was measured. The tests were carried out under the 1-MPa pressurized and unpressurized conditions, and until either air leak or buckling occurred.

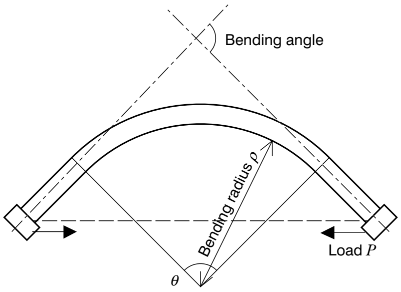

Figure 4 Bending test method.

Photo 2 Bending test.

3.3.2. Test Results

Figure 5 shows the relationship between the bending curvature and bending moment of each sample, obtained by the bending deformation tests.

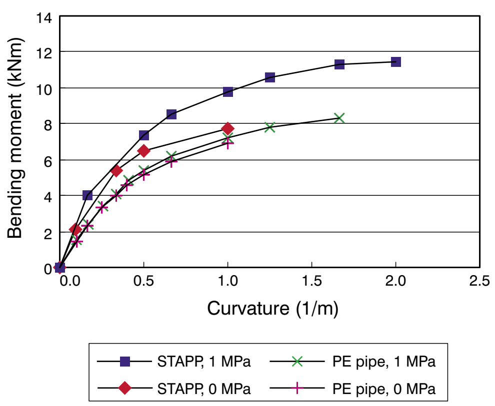

Figure 5 Relationship between curvature and bending moment.

The following could be confirmed from the results of the bending deformation tests.

- The bending rigidity of the STAPP is about 24 kNm^2, demonstrating that the pipe is twice as flexible as an all-polyethylene pipe with a thicker wall for the same working pressure having a bending rigidity of 56 kNm^2.
- The bending angle limit of the STAPP is not less than 80° with sufficient resistance against buckling, showing a bendability twice as large as that of a steel pipe of the same dimensions, when their bending angle limits are compared.

3.4 Axial Compression Characteristics

Axial compression test was carried out as part of earthquake resistance evaluation for the STAPP.

3.4.1. Sample and Test Procedure

STAPP and its inner polyethylene pipe, both 0.5 m and 1.0 m in length, were used in the test, where compression load was applied in the axial direction until buckling occurred, and the relationship between the displacement and axial compression force was measured. The tests were carried out under the 1-MPa pressurized and unpressurized conditions. Figure 6 and Photo 3 show a schematic and a scene of buckling of the axial compression test, respectively.

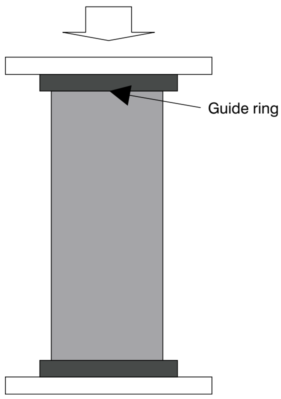

Figure 6 Schematic of axial compression test.

Photo 3 Axial compression test where buckling occurred.

3.4.2. Test Results

Figure 7 shows the relationship between the axial displacement and axial compression force measured using the 0.5-m long samples. The results confirm the following.

- The STAPP withstood buckling until the axial displacement reached a large deformation range (i.e. 7~10 %), demonstrating a large buckling deformation limit in comparison to a steel pipe of the same dimensions.
- The buckling resistance of the STAPP is larger than that of the all-polyethylene pipe by 30 %, showing some improvement in reinforcement due to the steel tape and the plastic jacket.
- The strain at buckling of the STAPP increased at 1-MPa pressurization than under unpressurized condition by about 15 %, indicating a slight improvement due to the steel tape.

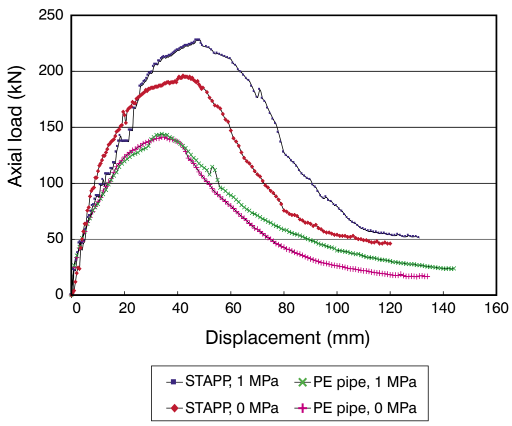

Figure 7 Relationship between axial deformation and axial compression force.

3.5 Shearing Characteristics

Shearing deformation test was carried out to evaluate the earthquake resistance of the STAPP.

3.5.1. Sample and Test Procedure

STAPP and its inner polyethylene pipe, each 2 m long, were used in the test. As shown in Figure 8, the sample was fixed at both ends, and displacement was given at the center portion to yield three-point-bending deformation, whereby shearing loads were applied on a shearing span of 200 mm in length to obtain the relationship between the displacement and load. The measurement continued under the 1-MPa pressurized and unpressurized conditions until the contained water began to leak.

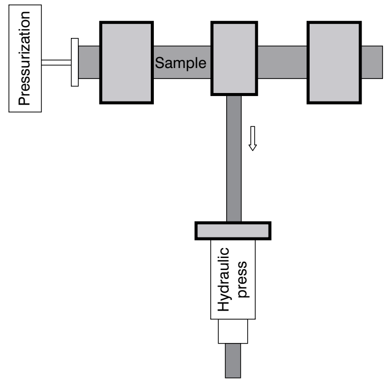

Figure 8 Setup for shearing deformation test.

3.5.2. Test Results

Figure 9 and Photo 4 show the results and a scene of the shearing test, respectively, from which the following could be confirmed.

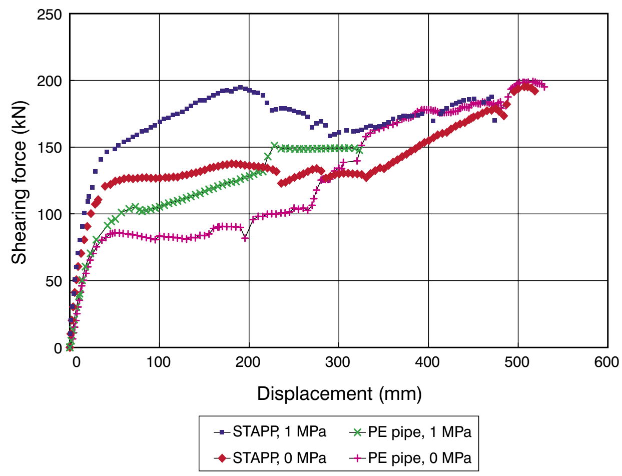

Figure 9 Relationship between shear deformation and shearing load.

Photo 4 Shearing test where breakdown occurred.

- The shearing elasticity of the STAPP is about twice that of the all-polyethylene pipe, demonstrating reinforcement improvements due to the steel tape and the plastic jacket. With respect to the presence of internal pressure, the difference was not very remarkable in terms of shearing elasticity.
- The crack-opening displacement due to shearing for the STAPP is equivalent to that for the all-polyethylene pipe when unpressurized, but raised by

about 40 % when pressurized, showing the effects such that the steel tape protects the polyethylene pipe thus relaxing localized concentration of the strain.

3.6 Tensile Characteristics

Tensile breakdown test was carried out to evaluate the earthquake resistance of the STAPP.

3.6.1. Sample and Test Procedure

The test samples, either hydraulically pressurized to 1-MPa or unpressurized, were to be tensile tested until breakdown. All-polyethylene pipe was also tested for the sake of comparison.

3.6.2. Test Results

Figure 10 shows the relationship between the tensile elongation and stress in the tensile breakdown tests, and Photo 5 a scene thereof. The following could be confirmed from the test results.

- The tensile breakdown elongation and the yield strain of the STAPP are 60 % or more and about 20 %, respectively, demonstrating that the pipe can follow large elongations and contractions.
- The tensile behavior was approximately the same for different samples, i.e. with or without steel tape reinforcement, or pressurized or unpressurized, confirming that the behavior largely depends on the tensile characteristics of polyethylene pipe.

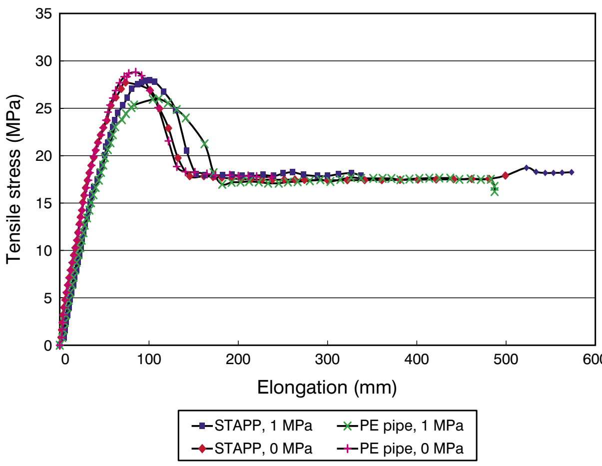

Figure 10 Relationship between tensile elongation and load.

Photo 5 Tensile test where breakdown occurred.

3.7 Impact Resistance Test

Rapid crack propagation test was carried out in conformity to ISO 1347 (S4 test) to confirm the impact resistance of the STAPP.

3.7.1. Sample and Test Procedure

A part of both the plastic jacket and the steel tape was removed from the sample to expose the polyethylene pipe, and a blade bit the exposed area to evaluate the behavior of crack propagation.

Then, polyethylene pipe was exposed at the end of a STAPP, and a crack was generated to see whether the steel tape can suppress crack propagation.

3.7.2. Test Results

Figure 11 shows the measured results of crack propagation limiting temperatures of polyethylene pipe, and Photo 6 a scene of the test. Major test results include the following.

- The polyethylene pipe showed no crack propagation whatever at normal temperatures, and it is not until in the low-temperature range of below –40°C that crack propagation was observed.
- In the test using the exposed end of a STAPP, the crack generated on the polyethylene pipe at –40°C, 2 MPa in internal pressure, propagated in the axial direction until it reached the region covered with the steel tape and plastic jacket. No abnormalities such as crack or peeling were found in the steel tape. Photo 7 shows the appearance of a sample after the test.

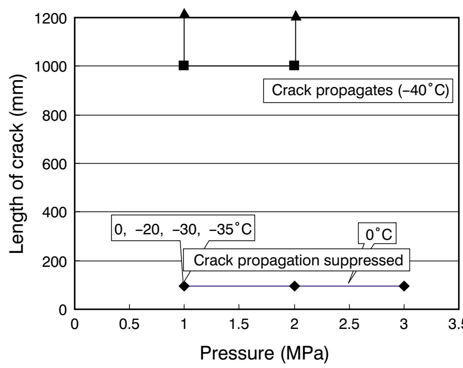

Figure 11 S4 characteristics of polyethylene pipe.

In an ordinary S4 test for polyethylene pipes, cracks propagate exhibiting a decaying wavy pattern. In the case of steel tape-armored pipe, on the contrary, cracks propagate linearly probably because the impact is impeded by the steel tape to disperse, and thus propagate through the steel tape into the plastic jacket. However, this does not seem to pose practical problems because cracks do not propagate unless below –40°C.

3.8 Inflammability Characteristics

3.8.1. Sample and Test Procedure

Inflammability verification test of the STAPP was carried out in conformity to IEEE 383. A pipe sample about 2-m

Photo 6 S4 test of all-PE pipe.

Photo 7 STAPP sample after S4 test.

long was fixed vertically onto the platform, and a burner was placed in a position 600 mm from the floor surface and 75 mm from the sample surface. The burner was lit for 20 min continuously, and subsequently the burnt length on the sample and the lasting time of residue flame were measured.

3.8.2. Test Results

It was confirmed that the pipe amply satisfies the qualifying standard of IEEE 383, with the results of 610 mm in burnt length, and 2 min 33 sec in the lasting time of residue flame. Photos 8 and 9 show the tests being carried out.

Photo 8 Inflammability test, burning sample.

Photo 9 Sample right after the burner was put out.

3.9 Gas Permeation Characteristics

3.9.1. Sample and Test Procedure

Gas permeation characteristics verification test was carried out for the STAPP using the setup shown in Figure 12. A gas receiving cylinder of stainless steel was installed to accommodate the pipe sample airtightly, and the pipe sample was pressurized by a methane gas supply to 1 MPa constantly. A gas chromatograph detector was connected to the receiving cylinder, carrying out long-term measurement of the built-up gas contained in the cylinder. Measurement was also done for an all-polyethylene pipe of the same dimensions for the sake of comparison.

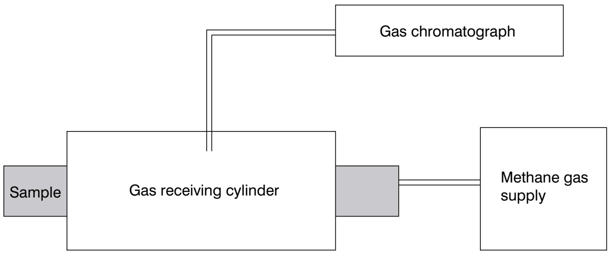

Figure 12 Setup for gas permeation test.

3.9.2. Test Results

Figure 13 shows the results of methane gas permeation test for the STAPP and the all-polyethylene pipe.

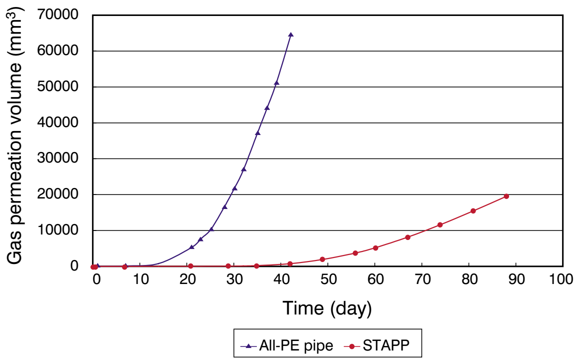

Figure 13 Results of methane gas permeation test.

From the test results, methane gas permeation rate per unit length was calculated as shown in Table 3. The gas permeation rate for the STAPP was about 3 % that of the all-polyethylene pipe, demonstrating a significant effect of gas shielding due to the steel tape armor.

Table 3 Rate of methane gas permeation.

Sample	Rate of methane permeation (ml/day/m)
Steel tape-armored polyethylene pipe	0.88
Polyethylene pipe	27.2

3.10 Long-Term Durability

Long-term durability test with a constant pressurizing period of 10000 hr was carried out to confirm the durability for internal pressure of the STAPP. It was confirmed that, as shown in Table 4, the pipe withstood without problems the long-term pressurization having an applied pressure more than twice the design pressure.

Table 4 Results of long term pressure test.

Test condition			Result
Temperature	Pressure	Time	
20°C	2.0 MPa	10000 hr	No problem
80°C	2.9 MPa	10000 hr	No problem
80°C	3.5 MPa	10000 hr	No problem
80°C	4.4 MPa	10000 hr	No problem

4. CONCLUSION

A medium- to high-pressure, flexible pipe for gas transmission has been developed that is suitable for long-piece transportation as well as long-distance installation. A composite structure pipe, such that stainless steel tapes for internal pressure reinforcement are provided over a thin-walled polyethylene pipe, was designed and prototyped, and the following conclusions were obtained through various performance evaluation tests.

1) A prototype pipe with an inside diameter of 156 mm for internal pressure of 1 MPa was used to measure the stress on the stainless steel tape under internal pressurization, and it was confirmed that the measured value agreed well with the theoretical design value. The flexibility of the pipe suitable for reel winding was also confirmed through bending characteristic test.
2) Internal pressure burst test, long-term internal pressure durability test, inflammability test and gas permeation test were carried out thus confirming that the pipe satisfies various performance requirements needed for medium- to high-pressure gas transmission.
3) Prototype pipe was evaluated in terms of axial compression characteristics, shearing characteristics, tensile characteristics and impact resistance, and it was confirmed that the steel tape-armored polyethylene pipe has superior earthquake resistance.

Hereafter, for practical implementation of medium- to high-pressure gas transmission line, we intend to confirm the conformity with related regulations and to develop installation methods of high efficiency and high reliability.

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