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Mechanical characteristics of fused cast basalt tube encased in steel pipe for protecting steel surface

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Abstract: Because of the various excellent characteristics of cast basalt materials, such as, anti-corrosion, anti-wearing, good hardness, high chemical stability, of which steel may not possess, the steel-basalt composite pipes are used in severe environments for compensating the defects of steel. The limit of bending moment with which steel-basalt composite pipe may safely endure was calculated and the limit curvature of the composite pipe in the safe range was presented. The application temperature of steel-basalt pipe was examined due to a different coefficient among basalt, mortar and mild steel.

Key words: basalt; fused cast basalt; steel-basalt pipe; bending; mechanical behavior

1 Introduction

Steel-basalt composite pipes have been used in industrial sites, compensating the defects of mild steels used under severe conditions, by applying remarkable features of cast refined basalt such as anti-corrosion, anti-wearing, good hardness and high chemical stability[1−3]. Steel-basalt composite pipes are being applied to various sectors[4]. Fig.1 shows a type of steel-basalt composite pipes. As shown in the figure, refined basalt is melted by heat and cast into a pipe, and the pipe is inserted to the inside of a mild steel, and then mortar is filled between the basalt and mild steels for them to be fixed. Mortar here plays not only an adhesive that makes steel material and basalt stick firmly together but also a buffer that absorbs a sudden change between the materials.

A steel-basalt composite pipe has great features of engineering; yet it includes basalt rather vulnerable than steel so the basalt pipe can be cracked or broken under excessive external force or change of installation space[5−6]. This study examined the basic properties of fused cast basalt, and made basalt plates to find out the mechanical features of basalt by conducting a 3-point bending test at ambient temperature, 200 ℃ and 300 ℃.

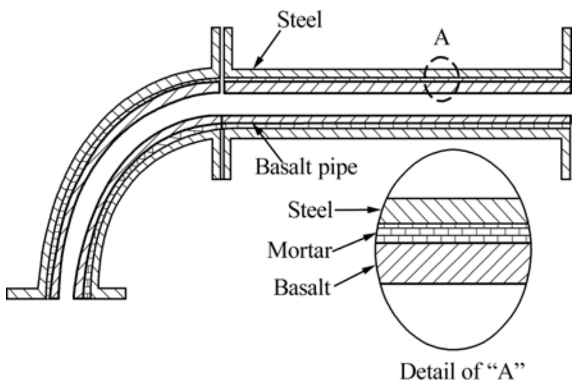

Fig.1 Steel-basalt composite pipe

And steel-basalt composite pipe prototypes were made to carry out 3-point bending tests by applying the bending moment on them, and the stress arising on mild steels was measured by a stress gauge, and then the measurement was compared with the results from interpretation. The behavior of the composite pipes was analyzed while the bending moment was applied to the

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pipes by external force, to present the limit of the curvature and bending moment for preventing any damage of basalt and to examine the temperature difference limit between the steel and basalt pipes for preventing mortar from being cracked or separated arising by the difference in the coefficients of thermal expansion.

2 Experimental

2.1 Materials

The cast basalt in this study should be selected from the raw basalt that has a close and even structure and few impurities. Table 1 shows the components of raw basalt ore used in this study. A cast basalt ore contained SiO_2 of 44%−46%, Al_2O_3 and Fe_2O_3 and FeO (iron oxide) nearly 12% and other components such as TiO_2, MgO, CaO, and P.P.P. Table 2 shows the mechanical properties of fused cast basalt[7−9].

Table 1 Components of raw basalt ore (mass fraction, %)

SiO_2	TiO_2	Al_2O_3	Fe_2O_3
40.0−48.0	1.5−3.5	11.0−16.0	3.0−6.0
FeO	MgO	CaO	P.P.P
5.0−10.0	8.0−12.0	9.0−13.0	7.0−12.0

Table 2 Mechanical properties of fused cast basalt

Properties	Value
Mohs hardness	8
Compressive strength/MPa	300−450
Bending strength/MPa	45
Density/(kg·m^{-3})	2 900−3 000
Coefficient of thermal expansion(0−100℃)/℃$^{-1}$	8×10^{-6}
Coefficient of thermal expansion(100−400℃)/℃$^{-1}$	9×10^{-6}
Coefficient of heat conductivity/(W·m^{-1}·℃$^{-1}$)	1.9−2.2
Elastic modulus/MPa	110
Melting point/℃	1 250
Insulation resistance/GΩ	10
Vicker's hardness (ISO409-1)	HV700−800

2.2 Methods

To explore the mechanical properties of cast basalt materials and steel-basalt composite pipes, the bending test of 3 points was carried out to check the displacement by load and the bending stress of them. Figs.2(a) and (b) show the dimensions of the cast basalt specimen for the bending test and the test points. Fig.3 shows the steel-basalt composite pipe and its 3-point bending test equipment.

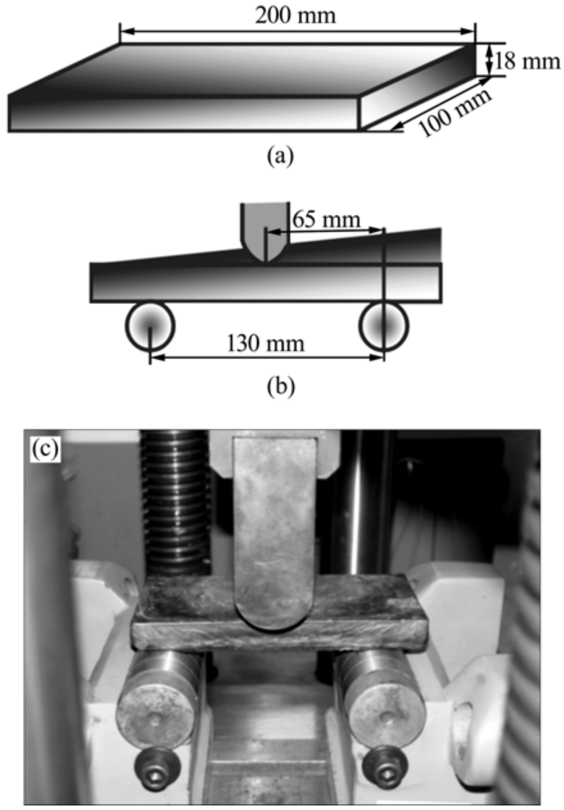

Fig.2 Bending test of fused cast basalt

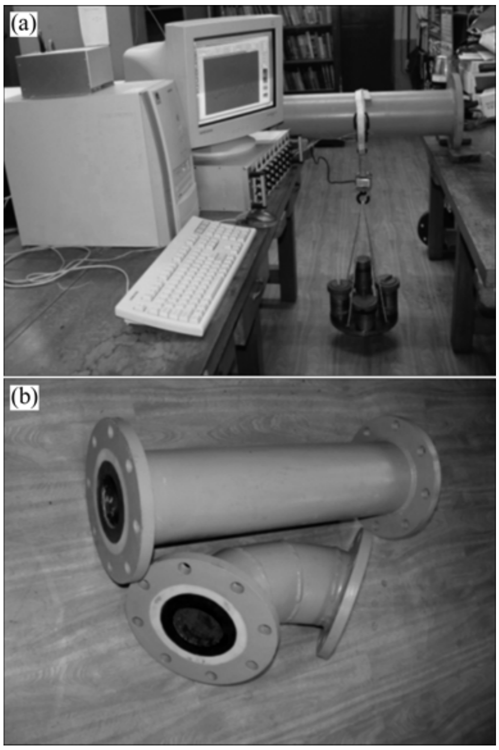

Fig.3 Steel-basalt composite pipes and its bending test

The specimens shown in Fig.2 were put in the electric furnace and heated to a specific temperature, and then the specimens were put on the 3-point bending tester to measure the load and the displacement. Fig.2(c) shows the tester applying load to the specimen.

In the steel-basalt composite pipe, the mild steel was 162 mm in outside diameter (D_s), 150 mm in inside diameter (D_{si}) and 6 mm in thickness; the basalt pipe was 130 mm in outside diameter (D_b), 90 mm in inside diameter (D_{bi}) and 20 mm in thickness; and the thickness of mortar was 10 mm. The length of straight pipe was 900 mm and the radius of elbow was 90°. The straight pipe was put on the testing bench horizontally and load was applied to the pipe by hanging a weight on the pipe center, for measuring the bending strain. Fig.4 shows the strain rosette fixed on the steel-basalt composite pipe. By using the strain rosette with weight to increase load, the stress detected from the rosette was entered to a computer through a strain amplifier and a data logger to obtain test results.

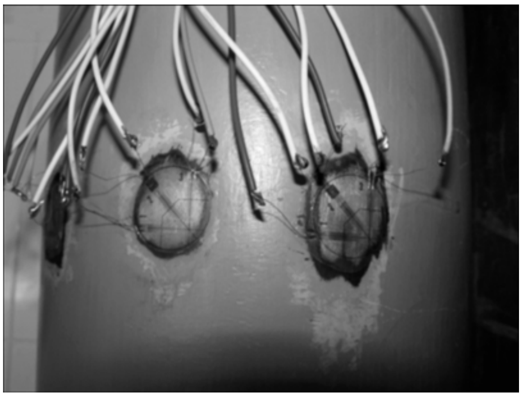

Fig.4 Strain rosette on steel-basalt composite pipe

3 Results and discussion

3.1 3-point bending test

3.1.1 Cast basalt material

Fig.5 shows the results of the 3-point bending test for the cast basalt material at room temperature. Total 6 specimens were made, and they showed the breaking

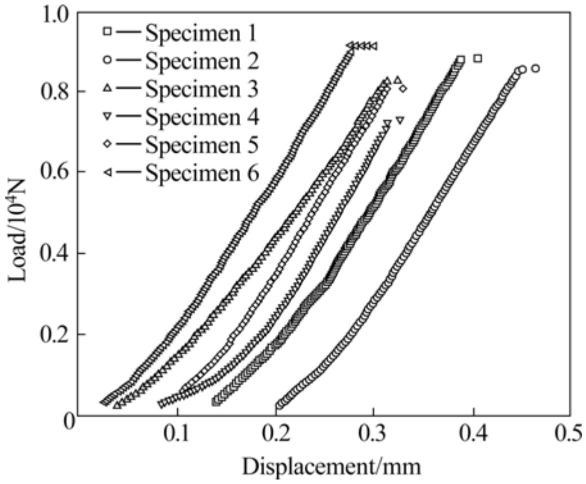

Fig.5 Results of bending test at room temperature

loads from 42.9 MPa to 53.8 MPa. Figs.6 and 7 show the results of the bending test at 200 ℃ and 300 ℃. The number of specimens tested at 200 ℃ was also 6 and the breaking loads were from 4 851 N to 7 291 N, showing the increased deviation. The stress converted from the loads was from 29.2 MPa to 43.9 MPa.

The number of the specimens tested at 300 ℃ was 5 and the breaking loads were from 1 911 N to 5 116 N, and the deviation between the loads had a big gap that the test was not considered to have reproducibility. The stress converted by the loads was from 11.5 MPa to 30.8 MPa.

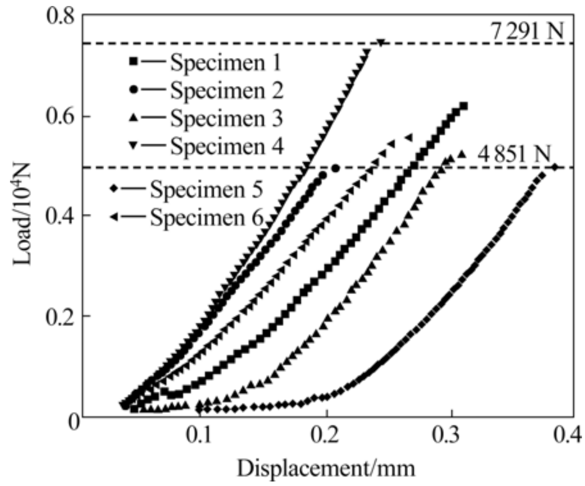

Fig.6 Results of bending test at 200 ℃

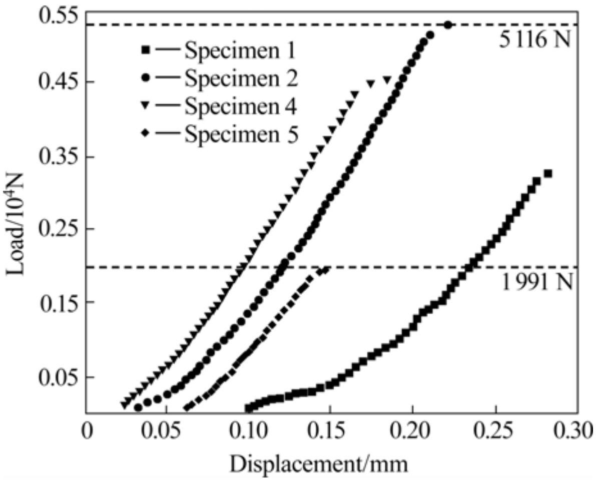

Fig.7 Results of bending test at 300 ℃

During the casting in the mould and heat treatment in the annealing furnace, the fused cast basalt formed different nucleation and crystallization with porosities and grain boundaries due to different surrounding conditions like temperature and chemical compositions. It is the reason that the deviation of bending test shows big gap with each individual specimen especially at high temperature[6, 10].

3.1.2 Steel-basalt composite pipe

Fig.8 shows the relationship between the loads applied to the composite pipe and the bending stress measured. The relationship shown in the figure is nearly linear. The dotted line is the relationship between the loads and the bending stress of mild steel with the same size as the steel-basalt composite pipes, and the full line is the calculated relationship of the composite pipes, and the dots on the full line are the measured values. The measured ones are generally smaller than the calculated ones although they are nearly close, and it is thought that the effect of mortar is the reason.

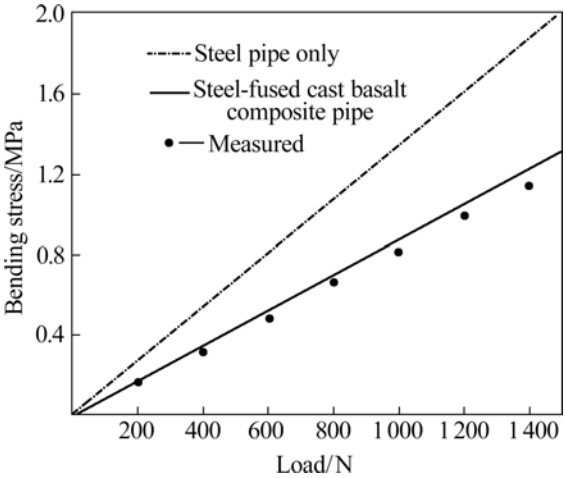

Fig.8 Results of bending test

3.2 Measurement of bending moment

To prevent any damage arising from steel-basalt composite pipes in industrial spots, the possible degree of load and the bending moment of the composite pipes should be examined to set up its safety standards before designing piping works. Fig.9 shows the deformity state of a vertical cross section when a composite pipe is applied by the bending moment (M). The degree of the deformity is proportional to the distance from the neutral surface; below the surface bending occurs; and above the surface compressive deformation occurs. In case that the radius of curvature is ρ, the curvature of the neutral surface, $1/\rho$, is expressed as follows, by the bending theory of a beam:

$$\frac{1}{\rho}=\frac{M}{E_sI_s+E_mI_m+E_bI_b} \tag{1}$$

where M is the bending moment, E_s, E_m and E_b are the elasticity coefficients of mild steel, mortar and basalt, and I_s, I_m and I_b are the 2nd moment of the sections of mild steel, mortar and basalt, respectively.

In case that the outside and inside diameters of the mild steel are D_s and D_{si}, respectively and those of the basalt pipe are D_b and D_{bi}, it can be expressed as follows:

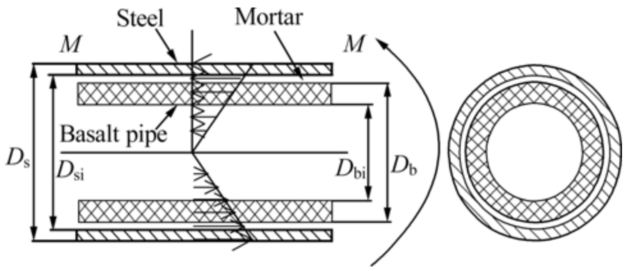

Fig.9 Bending stress of steel-basalt composite pipe

$$I_s=\frac{\pi(D_s^4-D_{si}^4)}{32}$$

$$I_m=\frac{\pi(D_{si}^4-D_b^4)}{32}$$

$$I_b=\frac{\pi(D_b^4-D_{bi}^4)}{32}$$

Basalt is more vulnerable than mild steel, and is strong to compressive stress and weak to bending stress like other brittleness materials, so it is thought to be proper to examine the bending stress only occurring on the basalt. The bending stress on the basalt pipe is expressed as follows:

$$\sigma_b=\frac{E_bM_y}{E_sI_s+E_mI_m+E_bI_b} \tag{2}$$

where y is the distance from the neutral surface. The maximum bending stress (σ_{bmax}) arising on the basalt pipe can be calculated by substituting y for $D_b/2$:

$$\sigma_{b\max}=\frac{E_bMD_b/2}{E_sI_s+E_mI_m+E_bI_b} \tag{3}$$

In general, the coefficient of elasticity of mortar (E_m) is so small, when comparing with that of basalt or mild steel, that it can be disregarded. The maximum bending stress occurring on the basalt is re-expressed as follows:

$$\sigma_{b\max}=\frac{E_bMD_b/2}{E_sI_s+E_bI_b} \tag{4}$$

The value above should not exceed the bending strength of basalt, 45 MPa, so the bending moment (M) applying to the composite pipe is restricted as follows:

$$M/(\text{N·mm})\leqslant\frac{90(E_sI_s+E_bI_b)}{D_bE_b} \tag{5}$$

The radius of curvature (ρ) is expressed as follows:

$$P/\text{mm}\geqslant\frac{D_bE_b}{90} \tag{6}$$

For example, in the case of the prototype, its values are applied to the formula: D_s=162 mm, D_{si}=150 mm,

D_b=130 mm and D_{bi}=90 mm, and E_s=200 GPa, E_b=110 GPa (the coefficient of elasticity). It can be found out that the calculated bending moment (M) should be less than 37.5 kN·m and the radius of curvature (ρ) should be more than 158.89 m.

3.3 Examination of application temperature

The following is to examine the application temperature through thermal contraction and expansion. As aforementioned, mild steel and basalt do not have the same trend of contraction and expansion if there is temperature change since the coefficient of thermal expansion of basalt is about 2/3 that of mild steel. The adhesion state between mild steel and basalt should be, thus, examined according to changes in temperature. In the case of decreased temperature, both mild steel and basalt become contracted. The contraction of the diameter of mild steels is larger than that of basalt pipes, and it leads to the bending stress on the mild steel and to the compressive stress on the basalt pipe and mortar. This change does not cause any problem because mild steels are strong to bending and mortar and basalt are strong to compression. On the contrary, in the event of the increased temperature, the expansion of the diameter of mild steels comes to be larger than that of basalt pipes, and it increases the distance between the mild steel and basalt pipe, that is, the thickness of mortar. If the increase of temperature exceeds a specific level, it is difficult for mortar to maintain its adhesion since mortar is weak to bending. The following is, thus, to figure out the limit of temperature increase.

The thickness of mortar (t_m) is (D_{si}−D_b)/2, and in case that temperature rises by T, the thickness can be expressed as follows:

$$t'_m=\frac{D_{si}(1+\alpha_s T)-D_b(1+\alpha_b T)}{2} \tag{7}$$

where α_s and α_b are the coefficients of thermal expansion of mild steel and basalt, respectively. As the coefficient of elasticity of mortar (E_m) is smaller than that of mild steel and basalt, the deformity of mortar in a direction of its thickness is expressed as follows:

$$\varepsilon_{mr}=\frac{D_{si}\alpha_s-D_b\alpha_b}{D_{si}-D_b}T \tag{8}$$

The stress to the direction of the mortar thickness can be, thus, formulated as follows:

$$\sigma_{mr}=E_m(\varepsilon_{mr}-\alpha_m T)=E_m(\frac{D_{si}\alpha_s-D_b\alpha_b}{D_{si}-D_b}-\alpha_m)T \tag{9}$$

where α_m is the coefficient of thermal expansion of mortar. The stress calculated by the formula should not exceed the bending strength of mortar (σ_{mf}). The increase of temperature (T) is, consequently, restricted to the value calculated as follows:

$$T\leqslant\frac{\sigma_{mf}}{E_m}\cdot\frac{(D_{si}-D_b)}{D_{si}(\alpha_s-\alpha_m)-D_b(\alpha_b-\alpha_m)} \tag{10}$$

For example, in the case of the prototype, its values are applied to the formula above: D_{si}=150 mm, D_b=130 mm, α_s=12×10^{-6}/℃, α_b=8×10^{-6}/℃, α_m=9.5×10^{-6}/℃, E_m=20 GPa, α_{mf}=30 MPa. The calculated result is $T\leqslant$ 52.63 ℃. So it can be thought that if a composite pipe was manufactured at room temperature (20 ℃), the application temperature should be restricted to below 72.63 ℃.

4 Conclusions

Steel-basalt composite pipes, as a pipe that enforces the strong points of steel such as toughness and strength and substitutes its weak points such as abrasion and corrosion for the advantages of basalt, such as, anti-corrosion and anti-wearing, were developed and have been used in various industrial sites. To find out the mechanical behavior of the composite pipes will be helpful to their designing and construction.

1) The bending moment that can be applied to steel-basalt composite pipes should be less than the value calculated by the following formula:

$$M/(\mathrm{N\cdot mm})\leqslant\frac{90(E_s I_s+E_b I_b)}{D_b E_b}$$

2) The radius of curvature of steel-basalt composite pipes should be the value more than the value calculated by the following formula:

$$P/\mathrm{mm}\geqslant\frac{D_b E_b}{90}$$

3) The application temperature of steel-basalt composite pipes should not exceed the increase range calculated by the following formula from the temperature of manufacturing:

$$T\leqslant\frac{\sigma_{mf}}{E_m}\cdot\frac{(D_{si}-D_b)}{D_{si}(\alpha_s-\alpha_m)-D_b(\alpha_b-\alpha_m)}$$

From the production process of steel-basalt composite pipes, it is desirable to standardize the thickness of basalt tube, thickness of mortar, diameter, inside diameter, outside diameter and thickness of mild steel pipes, flange size, location and number of bolt halls, radius of curvature of elbows and so forth so that the composite pipes will be used in a wider range of sectors thanks to the increased compatibility.

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