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TECHNICAL NOTE

# Double-ice-plug freezing using liquid nitrogen for water pipe repairs

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**ABSTRACT**
Accidentally a new method of water pipe repairs using liquid nitrogen freezing was discovered in 2008. Freezing water creates an ice plug to stop water flow. The new method uses double-ice-plug freezing instead of the world widely used single-ice-plug freezing. We have investigated the static sliding (shear) friction between the water pipe and the frozen ice-plug(s). The proposed method significantly increases water pressure in order to stop water flow. The experimented result shows that the ice adhesive strength of double-ice-plug freezing is roughly four times higher than that of single-ice-plug freezing. The unfrozen part of the water pipe plays a key role for achieving the high ice adhesive strength by taking advantage of water expansion upon freezing. The brief results were published in *Science Advances*. Further results are detailed in this note.

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**KEYWORDS**
Water pipe repair; liquid nitrogen; single-ice-plug; double-ice-plug



## Text

In order to repair water pipes, liquid nitrogen is used for forming an ice plug to stop the water flow. In order to shorten the repair time of water pipes, it is important to increase the ice adhesive strength. A new method accidentally discovered uses double-ice-plug freezing. The double-ice-plug is composed of the first ice-plug, unfrozen water, and the second ice-plug while the unfrozen water plays a key role for enhancing the ice friction. The unfrozen water eventually will be frozen where the third ice-plug is formed with the strong friction by water expansion upon freezing. The brief results were published in *Science Advances* (Takefuji and Okubo 2017) where it might be the world-first paper for water pipe repairs published in Science. We have investigated two water pipes (Ductile iron pipe cement lining and Ductile iron pipe powder coating). Figures 1 and 2 depict the single-ice-plug freezing (Hu et al. 2014) and the double-ice-plug freezing, respectively. Table 1 shows the summary of the experimented results. From our experiments, after forming the third ice-plug, strong friction using three ice plugs was achieved.

The recent discovery of ice friction was reported by Lyu, Bergseth, and Olofsson (2016) and by Gouni (2011) where ice friction peaks at -15 °C or -13 °C, respectively. Taking advantage of the formation of the third ice-plug by water expansion upon freezing, the highest ice adhesive strength (3 MPa) was achieved by the proposed double-ice-plug freezing. We may be able to achieve more than 3 MPa by the double-ice-plug freezing. However, it is prohibited in Japan to experiment above 3 MPa. The ice adhesive strength of the single-ice-plug freezing is measured from 0.4 MPa to 0.9 MPa as shown in Table 1. Our experiments show that the ice adhesive strength of double-ice-plug freezing is roughly four times or at least three times higher than that of the single-ice-plug freezing. In other words, without extra cost, water pipe repairs can be dramatically improved by the proposed double-ice-plug freezing. Furthermore, the double-ice-plug freezing requires less liquid nitrogen than the single-ice-plug because of the unfrozen water pipe.

## Methods

### *Double-ice-plug freezing*

Single-ice-plug freezing is depicted in Figure 1 where *B* indicates the total length of frozen water pipe using liquid nitrogen in a single container. Figure 2 shows double-ice-plug freezing using two containers where *A* denotes the length of the unfrozen part of the water pipe between two containers. The unfrozen part of the double-ice-plug freezing between two containers plays a key role for successfully enhancing the ice adhesive strength by water expansion upon freezing.

In the single-ice-plug and double-ice-plug freezing, the water pressure was measured when the ice-plug slid. In the single-ice-plug and double-ice-plug freezing, the static sliding (shear) friction between the water pipe and the frozen ice-plug was measured.

Experimental procedure: the equipment used in the experiment is detailed in Figure 3.

1. Fill water in the pipe with 0.2 MPa water pressure at both ends

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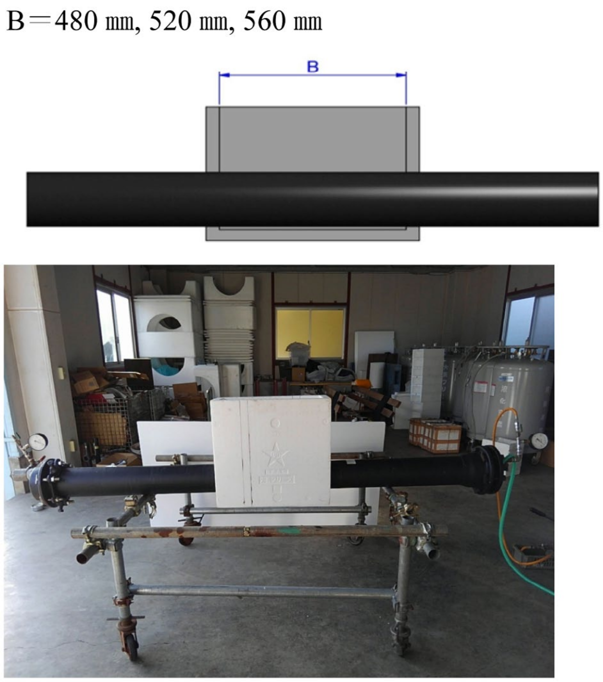


Figure 1. Single-ice-plug freezing: $B = 480$, 520 and 560 mm.

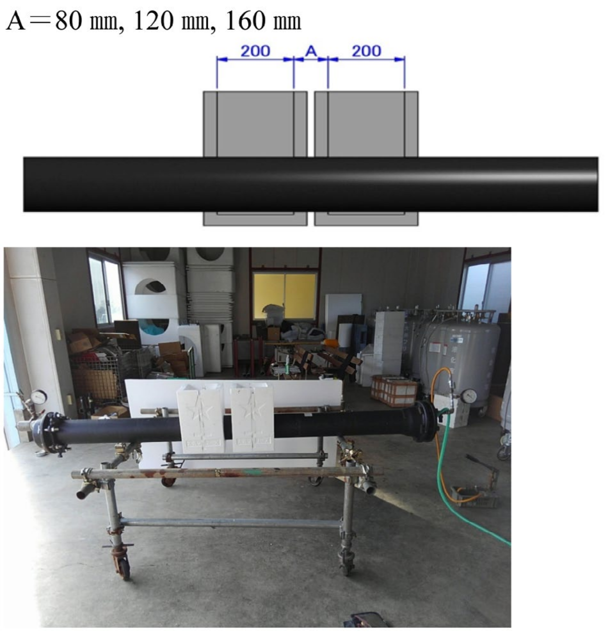


Figure 2. Double-ice-plug freezing: $A = 80$, 120 and 160 mm.

Table 1. Experiment results: cement: Ductile iron pipe cement lining (inner diameter: φ146, outer diameter: φ169, thickness: 7.5, cement: 4.0) (mm); pwd: Ductile iron pipe powder coating (inner diameter: φ152, outer diameter: φ169, thickness: 7.5, cement: 1.0) (mm).

| No. | Pipe | T rial | Freezing | Unfrozen length (*A*) | Frozen length (*B*) | Pressure (MPa) | Frozen time (min) | Temp(°C) | Water temp (°C) | Air pressure (hPa) | Liquid nitrogen (ℓ) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | cement | 1st | single | 80 | 480 | 0.5 | 34 | 22.8 | 22.3 | 1014 | 72 |
| 2 | cement | 2nd | single | 80 | 480 | 0.7 | 34 | 22.8 | 21.8 | 1015 | 78 |
| 3 | cement | 1st | single | 120 | 520 | 0.75 | 35 | 22.8 | 22.3 | 1014 | 78 |
| 4 | cement | 2nd | single | 120 | 520 | 0.58 | 33 | 22.8 | 21.8 | 1015 | 74 |
| 5 | cement | 1st | single | 160 | 560 | 0.58 | 33 | 21.8 | 21.7 | 1015 | 76 |
| 6 | cement | 2nd | single | 160 | 560 | 0.41 | 33 | 21.8 | 23.2 | 1020 | 74 |
| 7 | cement | 1st | double | 80 | 480 | 3 | 34 | 21.8 | 21.7 | 1015 | 66 |
| 8 | cement | 2nd | double | 80 | 480 | 3 | 35 | 26.2 | 23.2 | 1020 | 58 |
| 9 | cement | 1st | double | 120 | 520 | 3 | 36 | 25 | 23.2 | 1020 | 66 |
| 10 | cement | 2nd | double | 120 | 520 | 3 | 37 | 28.5 | 22.3 | 1018 | 64 |
| 11 | cement | 1st | double | 160 | 560 | 3 | 34 | 25 | 23.2 | 1020 | 66 |
| 12 | cement | 2nd | double | 160 | 560 | 3 | 34 | 28.5 | 22.3 | 1018 | 66 |
| 13 | pwd | 1st | single | 80 | 480 | 0.6 | 36 | 21.6 | 22.8 | 1011 | 70 |
| 14 | pwd | 2nd | single | 80 | 480 | 0.9 | 38 | 20.1 | 21 | 1010 | 72 |
| 15 | pwd | 1st | single | 120 | 520 | 1.3 | 37 | 21.6 | 22.8 | 1011 | 72 |
| 16 | pwd | 2nd | single | 120 | 520 | 0.9 | 33 | 20.1 | 20.9 | 1010 | 70 |
| 17 | pwd | 1st | single | 160 | 560 | 0.52 | 33 | 20 | 22 | 1019 | 78 |
| 18 | pwd | 2nd | single | 160 | 560 | 0.95 | 33 | 20.6 | 21.7 | 1020 | 78 |
| 19 | pwd | 1st | double | 80 | 480 | 3 | 36 | 20 | 22.0 | 1019 | 62 |
| 20 | pwd | 2nd | double | 80 | 480 | 3 | 33 | 12.2 | 14.7 | 1021 | 58 |
| 21 | pwd | 1st | double | 120 | 520 | 2.6 | 36 | 23 | 21.5 | 1020 | 64 |
| 22 | pwd | 2nd | double | 120 | 520 | 3 | 36 | 23 | 21.5 | 1020 | 66 |
| 23 | pwd | 1st | double | 160 | 560 | 3 | 32 | 22.2 | 22.6 | 1019 | 66 |
| 24 | pwd | 2nd | double | 160 | 560 | 2.95 | 35 | 22.2 | 22.6 | 1019 | 66 |

2. Measure the temperature of water
3. Set a container for single-ice-plug freezing
Set two containers for double-ice-plug freezing
4. Fill liquid nitrogen in the container(s)
5. Detect the completion of freezing water
6. Keep water pressure at 0.41 MPa for 10 minutes
7. Decrease water pressure at the secondary side until 0.1 MPa
8. Increase water pressure at the primary side until 3.0 MPa

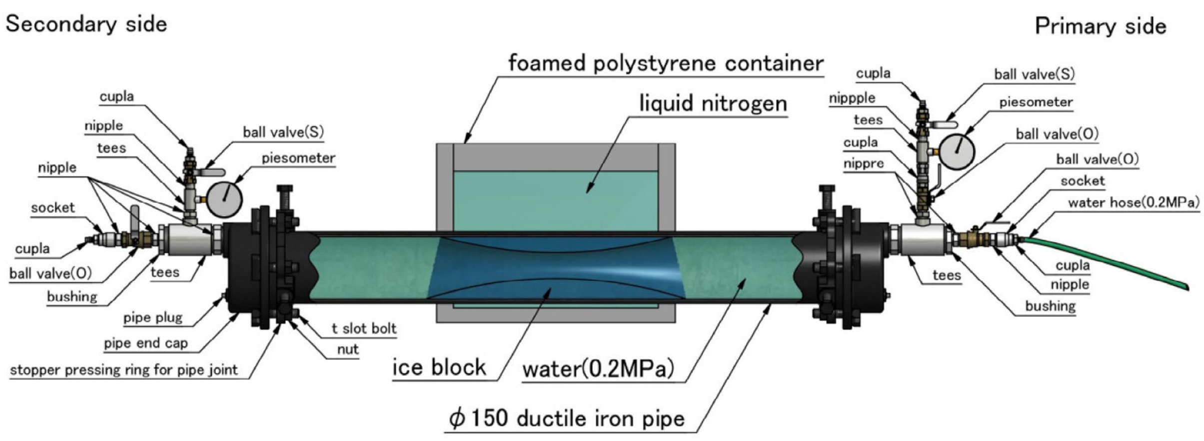


**Figure 3.** Detailed ice-plug freezing.

## Conclusion

Although the frozen time of the double-ice-plug is the same as that of the single-ice-plug, the ice adhesive strength or the ice friction of the double-ice-plug is roughly four times higher than that of the single-ice-plug. Furthermore, the double-ice-plug freezing requires less liquid nitrogen than the single-ice-plug.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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