

# APPLICATION OF PVC MEMBRANE ON PITCHED ROOFS FOR MUSEUM ROOF GARDENS

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A new museum, designed by Mr. I. M. Pei of New York, was completed in August 1996 in the mountains near Kyoto, Japan. It will open in October 1997 in cooperation with the New York Metropolitan Museum.

A regulation in Japan's Nature Protection Act prevented Pei from building a new large structure aboveground; therefore, he decided to building most of the museum underground in harmony with environmental scenery. After the building was completed, most of the roofs were covered with 1 m (3.3 feet) of soil and planted with trees and bushes so that the museum would restore the shape of mountains. The roofs were composed of many surfaces with irregular sizes, and PVC membranes were applied to these roofs, which had a total area of 7,000 m<sup>2</sup> (75,350 square feet).

The most important requirement for a long service life is high reliability of waterproofing, especially the quality of the membrane seams. This paper will show that test-cut evaluation of welding is essential for airtightness and that vacuum testing is useful for inspecting welded seams.

## KEYWORDS

Application quality, double membranes, green roof, hot-air welding, pitched roof, PVC membrane, roof garden, singly roofing, vacuum test, worker training.

## INTRODUCTION

A new museum, designed by Mr. I. M. Pei of New York, was completed in August 1996 in the mountains near Kyoto, Japan. It will open in October 1997 in cooperation with the New York Metropolitan Museum. A regulation in Japan's Nature Protection Act prevented Pei from building a new large structure aboveground; therefore, he decided to building most of the museum underground in harmony with environmental scenery. After the building was completed, most of the roofs were covered with 1 m (3.3 feet) of soil and planted with trees and bushes so that the museum would restore the shape of mountains (Figure 1).

To restore the mountains' shape, the roofs were composed of many surfaces with irregular sizes. PVC membranes, which have been used in many roof gardens in Switzerland and Germany, were applied to these roofs, which had a total area of approximately 7,000 m<sup>2</sup> (75,350 square feet). The most important requirement for a long service life is highly reliable waterproofing, especially the quality of the membrane seams.

The scale of the museum is shown in Table 1.

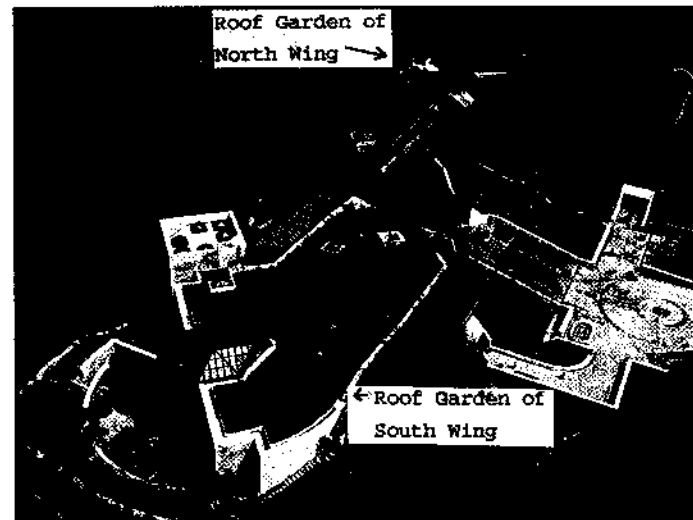


Figure 1. Miho Museum covered with green roof.

Scale of Museum	
Site Area	1,002,000 m <sup>2</sup> (10,785,430 ft <sup>2</sup> )
Construction Area	9,240 m <sup>2</sup> (99,460 ft <sup>2</sup> )
Total Area	20,780 m <sup>2</sup> (223,675 ft <sup>2</sup> )
Floors	one aboveground, two underground

Table 1: Scale of museum.

## BUILD UP OF ROOFING

The roofs were composed of many differently pitched surfaces; the slope ranged from 10 to 45 degrees, as shown in Figure 2. It was difficult to apply hot bitumen to the roofs because of the danger of working with hot bitumen on steeply sloped roofs. Because most of the roofs were more than 10 m (33 feet) long and because of the necessity of preventing protection concrete and soil from slipping as a result of gravity, Pei changed the shape to a combination of horizontal and pitched substrates, as shown in Figure 3. More than 500 concrete blocks were added to the horizontal substrate, as shown in Figure 2.

The build-up of the roof is illustrated in Figure 4. The concrete substrate was coated with a mixture of cement mortar and acrylate emulsion for waterproofing. Before PVC membranes were applied, a separation layer of polyester fiber was put on the substrate in order to prevent the migration of PVC



Figure 2. Substrate of pitched roofs with concrete blocks.

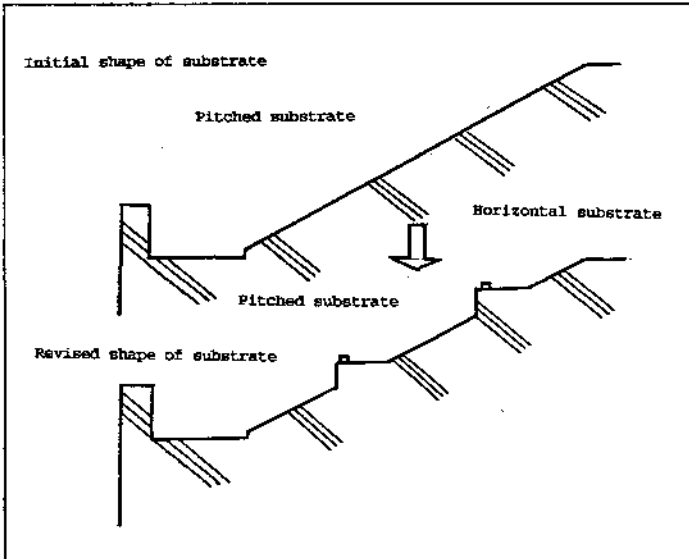


Figure 3. Change of substrate.

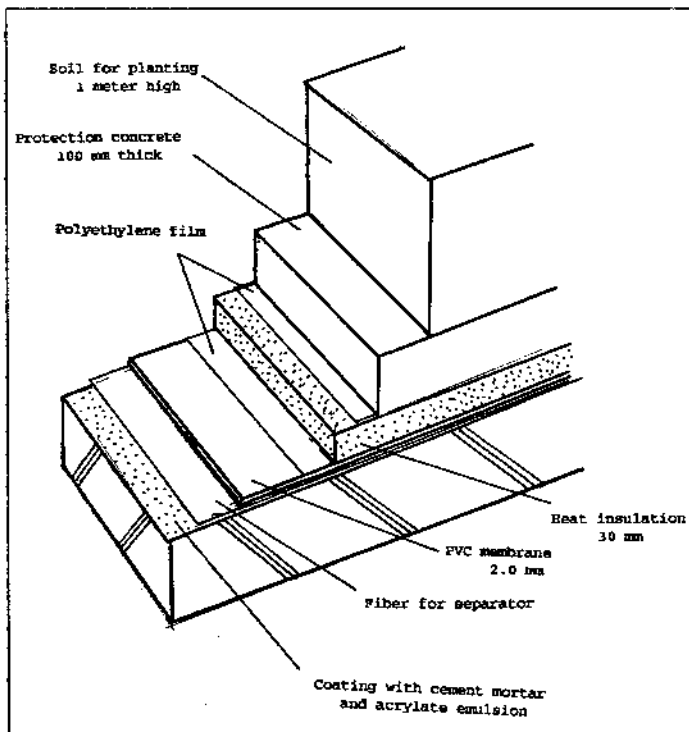


Figure 4. Built-up roof.

membrane plasticizer into the substrate coating. A 2-mm (0.06-inch) single-ply PVC membrane, reinforced with glass fiber, was loosely laid on most of the pitched roofs, and double membranes were also laid on horizontal roofs near parapets, as illustrated in Figure 5. The PVC membrane was mechanically fastened with steel bars at the cant of the vertical to prevent membrane slippage (Figure 6). In addition, a 4-mm (0.17-inch-) diameter PVC cord was welded on the membrane at the upper side of fastening bars. PVC cords increase the resistance to membrane pullout caused by the fastening bars, as shown in Table 2.

Pullout strength from fastening bars	
	Pullout strength:kgf(N)
between fastening screws, without PVC cord	6.1 kg (0.62 N)/25 mm [13.5 lbf/in (0.14 lbf)]
between fastening screws, with PVC cord	47.4 kg (4.84 N)/25 mm [104.5 lbf/in (1.09 lbf)]
at fastening screws, without PVC cord	26.6 kg (2.71 N)/25 mm [59 lbf/in (0.61 lbf)]
at fastening screws, with PVC cord	27.3 kg (2.79 N)/25 mm [60 lbf/in (0.63 lbf)]

Table 2: Pullout strength from fastening bars.

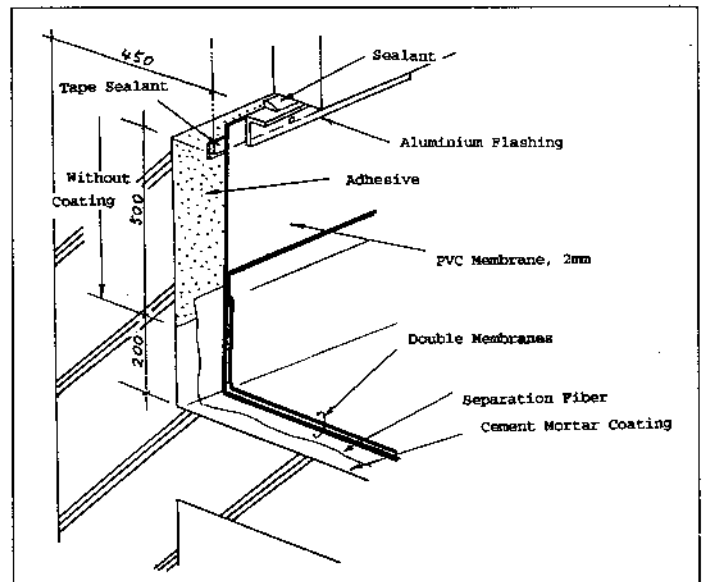


Figure 5. Double membranes on horizontal roof.

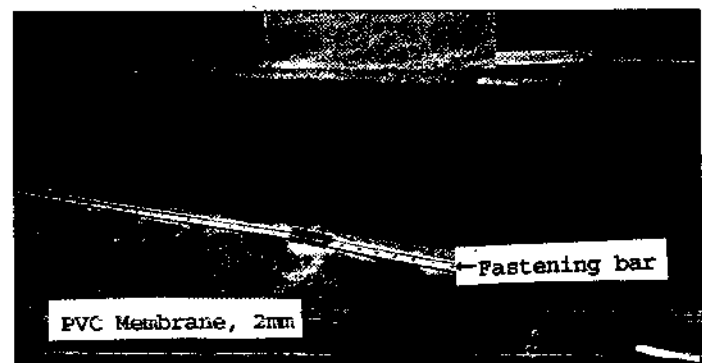


Figure 6. Fastening bar at the cant.

Following the application of 30-mm- (1.19-inch-) thick polystyrene insulation, protection concrete with steel reinforcement bars was put on the insulation (Figure 7). All roofs were then covered with 1 m (3.3 feet) of soil for planting.

Because it is impossible to repair any defects after the roof has been covered with soil, the waterproofing—especially the seams of the PVC membranes—had to be absolutely reliable.

Double membranes of PVC roofing can be more reliable than a single membrane. When edges of double membranes are joined by hot-air welding—every 40 to 50 m<sup>2</sup> (430 to 540 square feet), for instance—it is possible to discover any defect in the welded membranes by using a vacuum test, a technique employed in civil engineering (Figure 8). When the upper membrane is applied on the welding seam of the lower membrane, it is possible to detect any defect of the welding seam using a vacuum test (Figure 9). Because a double membrane system is naturally more expensive than a single membrane system, double membranes were limited to the horizontal roofs near the parapet and the welded seams of single-ply roofing.

The upper membrane has an embossment of small bumps or “knobs” on its lower side (Figure 10) to facilitate airflow between the membrane surfaces for a vacuum test.

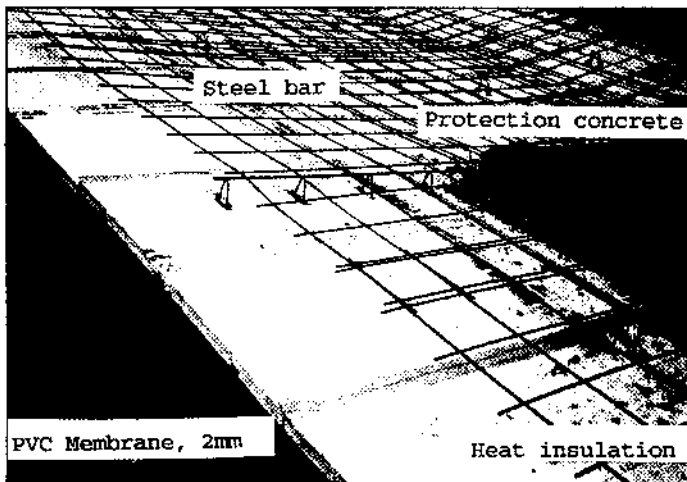


Figure 7. Built-up Roofing.

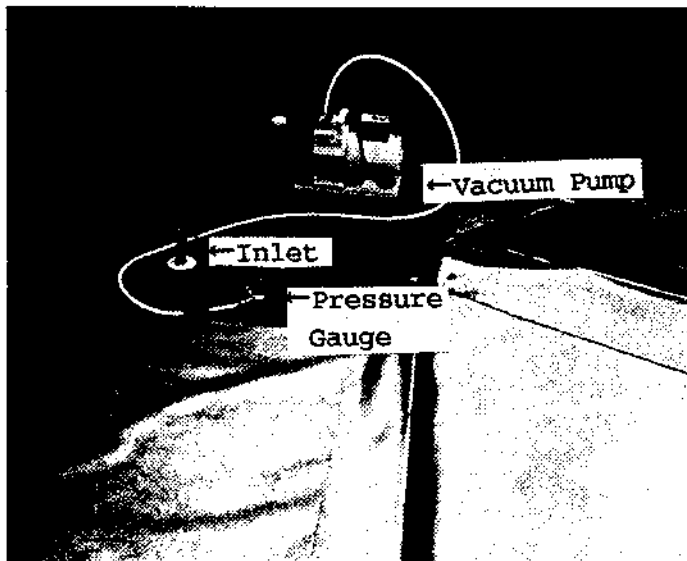


Figure 8. Vacuum Test: Type 1.

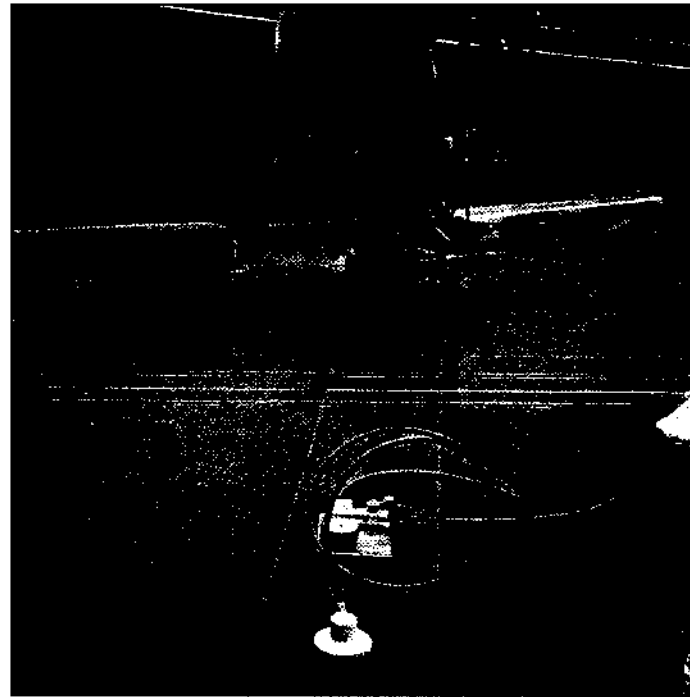


Figure 9. Vacuum test for double membranes on joint welding.

## DESCRIPTION OF MEMBRANES

The PVC membranes selected for the roofing are composed of plasticized PVC with fiberglass carrier and have the properties, including root-resistance, outlined in Table 3.

Regarding root resistance, another test was carried out in Germany in 1986. The results show that the PVC membrane had no root penetration after for four years (Figure 11); 85/15 bitumen, which was used as a control, had more than 160 roots penetrating the membrane in the 800- by 800-mm (32- by 32-inch) planting box.

## MOCK-UP TEST

A concrete substrate, similar to the actual roof, was prepared for a mock-up test of the PVC membrane application (Figure 12). The mock-up was prepared to certify the high reliability of the waterproofing provided by the PVC membranes and the high quality of the hot-air seam welding, and confirmation of the vacuum test for double membranes.

It was essential to train workers on hot-air welding techniques before actual application because skillful workers in Japan are generally familiar with solvent welding rather than hot-air welding. Only occasionally do they use a hot-air welder for PVC membranes. Solvent welding is perceived to

Properties of Membrane	
Size	2.0 mm by 2.0 m by 10.0 m (0.07 inches by 6.6 feet by 33 feet)
Color	Signal red/Dark grey
Elongation	250%
Tensile Strength	98 kg (10 N)/mm <sup>2</sup> (1450 psi)
Root Resistance	requirement met for SIA 280/11

Table 3: Properties of Membrane.

be more efficient for roofing application. However, with solvent welding, the seam strength just after welding is very low, and the seams have to be protected for two or three days in order to provide the high strength required of them.

Only hot-air welding by hand welder and automatic welders was used for PVC membranes. The definition of welding conditions, the vacuum test for double membranes, and worker training were the main purposes of the mock-up application.

#### Welding Conditions of Hand Welder

Hot-air welding by hand is required for detail work and small roof areas. Workers were able to adjust the hot-air temperature with a control button, according to the manual issued by the membrane manufacturer. It was important that workers had experience so that they welded correctly and so that they knew how to test the quality of the PVC seams they made. Sometimes voltage for the welder goes down at the site, and sometimes ambient temperature may become very low or very high; in these situations, workers have to know how to modify their welding method, reviewing test cuts of the welded seam.

The standard of welding was confirmed by three workers and a supervisor who was dispatched for training from Switzerland. Figure 13 shows the strength of the welded seams that they made with a 40-mm (1.63-inch) nozzle and the hot-air welder temperature control 6.5 and 7.

All welded seams were pulled to determine their integrity; the results are shown in Figure 15.

#### Welding Conditions of Automatic Welder

Certain automatic welders have three adjustable parameters of hot-air temperature, welding speed, and airflow. The owners manual gave combinations of the parameters as appropriate welding conditions to be adjusted for ambient temperature. The trial welding for PVC membrane seams with and without embossed knobs was made with automatic welders at various combinations of operating conditions. As a result of the trial, as shown in Figure 14, it is possible to say that all peel strengths were almost the same, but seam integrity at 440°C 1.7 m/min (824°F 5.6 feet/minute) (Figure 15) was appropriate while it was not appropriate at 400°C 1.5 m/min (752°F 4.9 feet/minute) (Figure 16). It is essential to inspect seam integrity under these operating conditions. Especially careful inspection of the welded seam at the beginning of the operation is also required.

#### Sealant

It is supposed that a small volume of air flows in from the edge of a PVC membrane through glass fibers. Sealant should be applied at the edge of membranes to stop airflow from outside. Although PVC paste is generally used for sealant for conventional roofing in Japan, a modified silicone sealant was applied instead after a comparison test in which both materials and their adhesion to PVC membrane were carefully investigated.

#### APPLICATION QUALITY

The actual application of PVC membranes on the site began in August 1995 and finished in February 1996. During these eight months, some workers left for other sites to make another application, and some new workers came to the site. Training programs for newcomers and strict inspection of

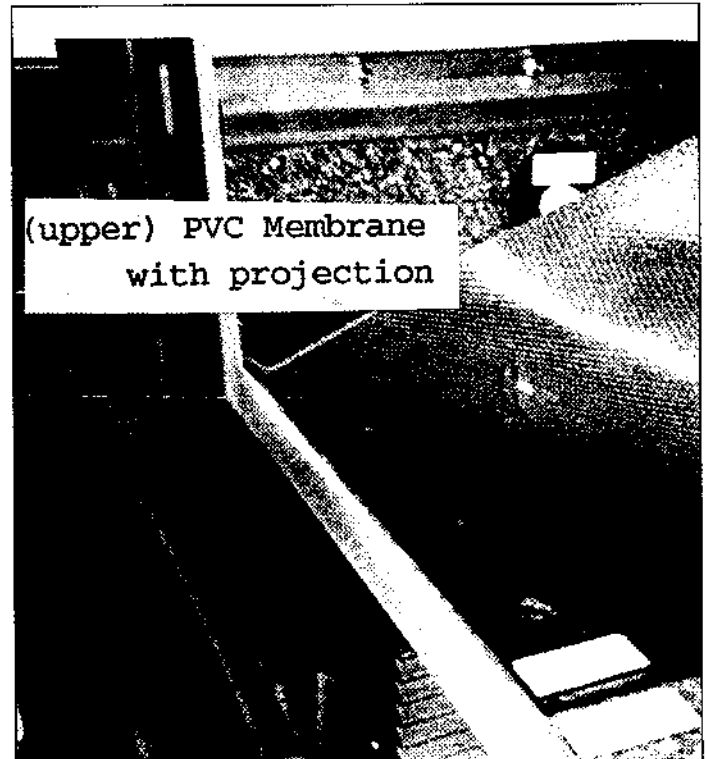


Figure 10. Double membranes; (upper) PVC membrane with projection, (lower) PVC membrane without projection.



Figure 11. Root resistance of PVC membrane.

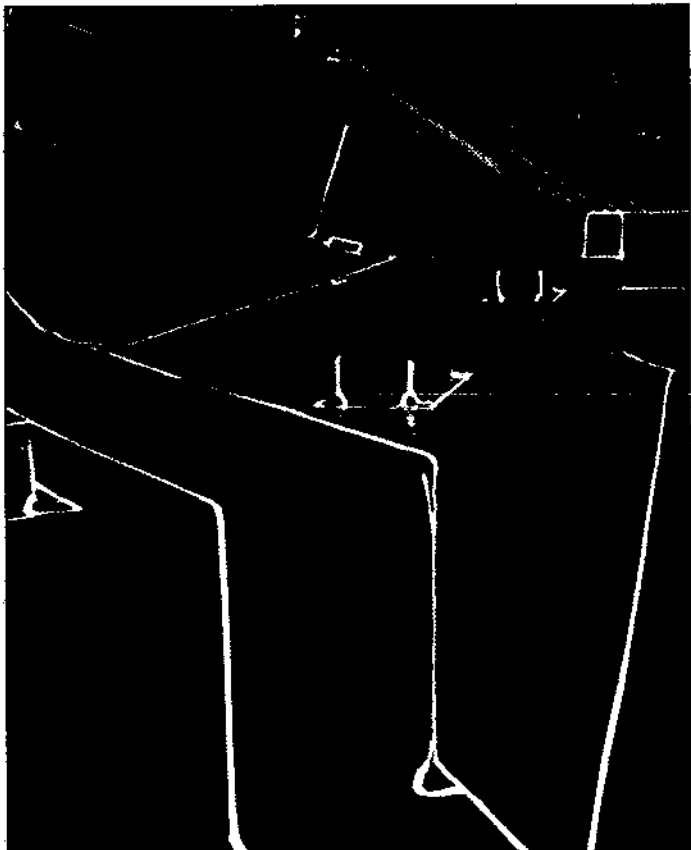


Figure 12. Mock-up applied with PVC membrane.

welded seams using the vacuum test were absolutely essential to certify application quality at the site.

**Training Programs for Newcomers**

Before newcomers began to work at the site, they had to receive two days of training regarding the operation of hot-air welders. By the end of the training, they had to make a 40-by 1000-by 1000-mm (40-inch) envelope of PVC membrane by welding the perimeter edges of a double membrane, which keeps vacuum for 10 minutes, according to the previously mentioned vacuum test. If the workers passed the vacuum test, they could start actual application. If not, they had to be engaged in jobs other than welding.

**Vacuum Test for Seam Welding**

Vacuum tests make it easy to discover defects in a seam. The following three tests were used to inspect seams:

- Test 1: Vacuum test for double membranes using PVC inlet.
- Test 2: Vacuum test for double membranes on seam welding and inner/outer corners using a needle.
- Test 3: Vacuum test for a single-ply membrane on seam welding using a transparent plastic box.

In Tests 1 and 2, air pressure between the double layers is decreased to 15 in Hg (7 psi) [380 mm Hg (0.5 bar)] with a vacuum pump and should not increase more than 20 percent after 15 minutes. If it increases more than 20 percent, it is concluded that there must be a defect at seam welding. Figure 17 shows the pressure increase for Test 1 during the mock-up test.

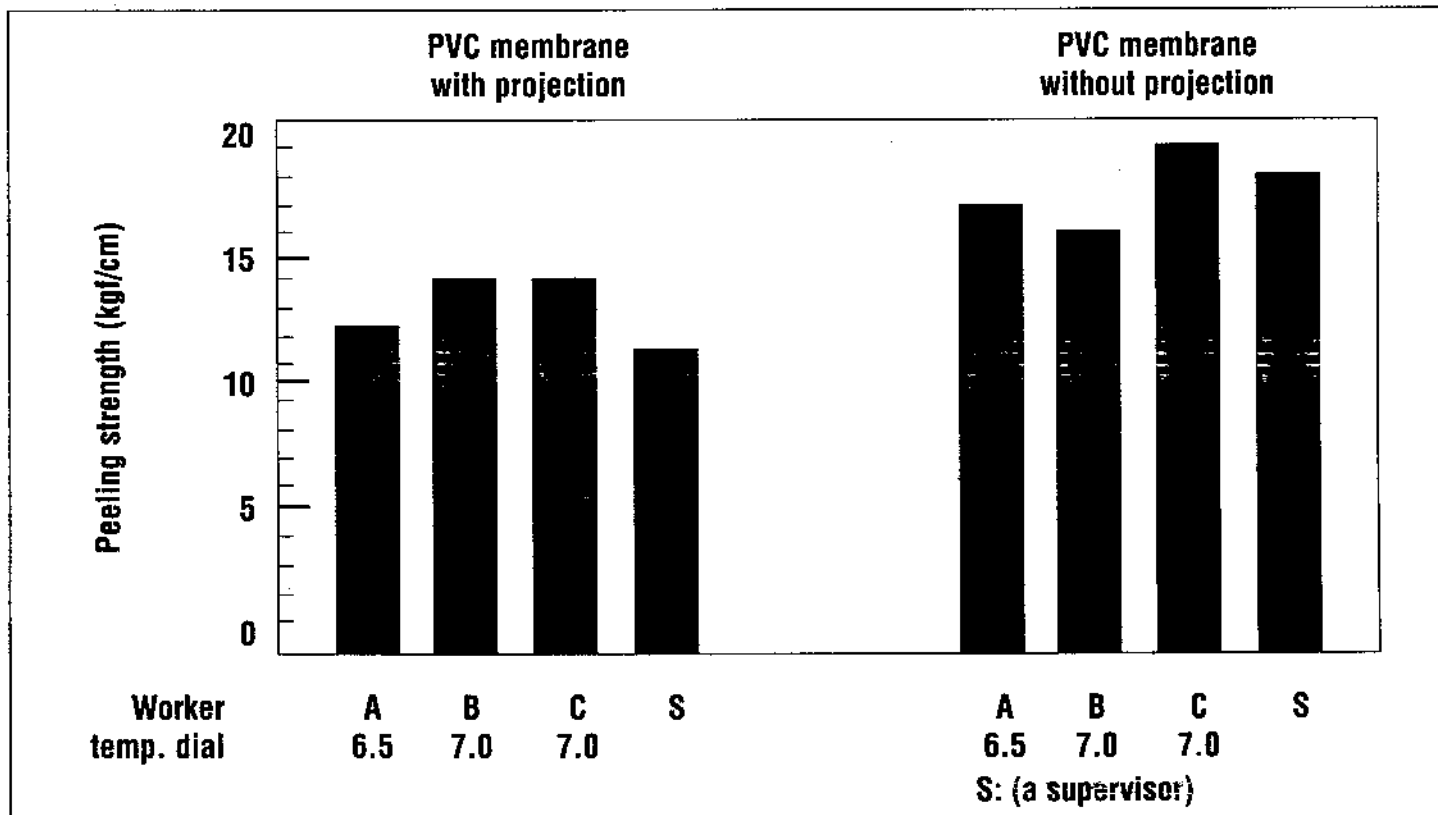


Figure 13. Peeling strength of welding joint with hand welder.

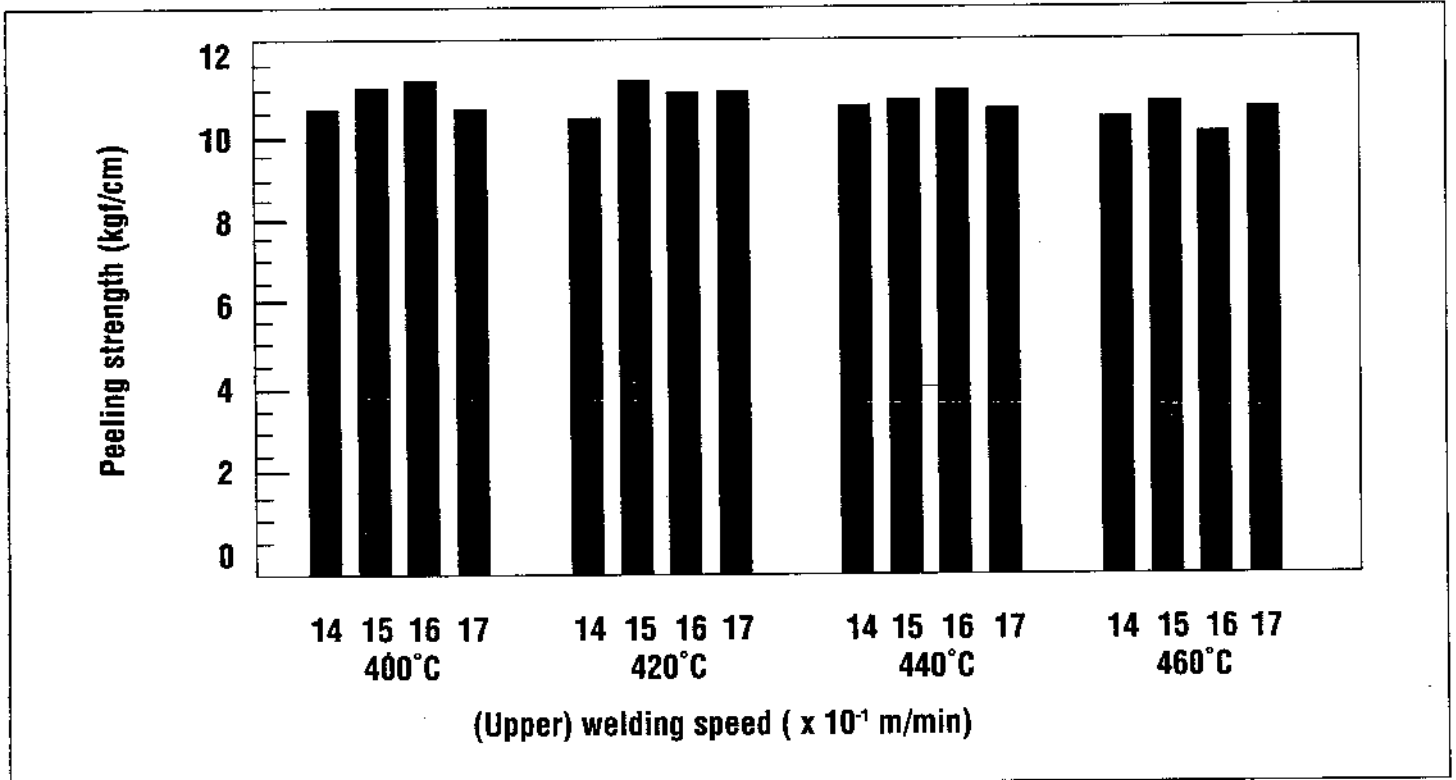


Figure 14. Peeling strength of welding joint with automatic welder (PVC membrane without projection).

In Test 3, a drop of soapsuds is placed on the welded seam edge. There should be no movement of the soapsuds caused by airflow under decreased pressure of the plastic box.

**Daily Quality Control**

- The appropriate welding conditions should be carried out strictly every day by every worker. Each morning before actual application, every worker made a trial welding with a hand welder and kept a record of the welding conditions together with his or her welding sample.
- Trial welding by automatic welders was carried out every morning in the same manner.

- Every seam was inspected by a vacuum test using an inlet or a needle. If the pressure increase was within 20 percent of initial vacuum pressure of 15 in Hg (7 psi) [380 mm Hg (0.5 bar)] (Figure 17), the final pressure was recorded on daily quality control chart. If not, a defect was looked for by vacuum test using a plastic box and was repaired with small patch of PVC membrane. Finally, the vacuum test was carried out again to certify the welded seam's airtightness.

**CONCLUSION**

For a long service life, PVC membrane roofing for roof

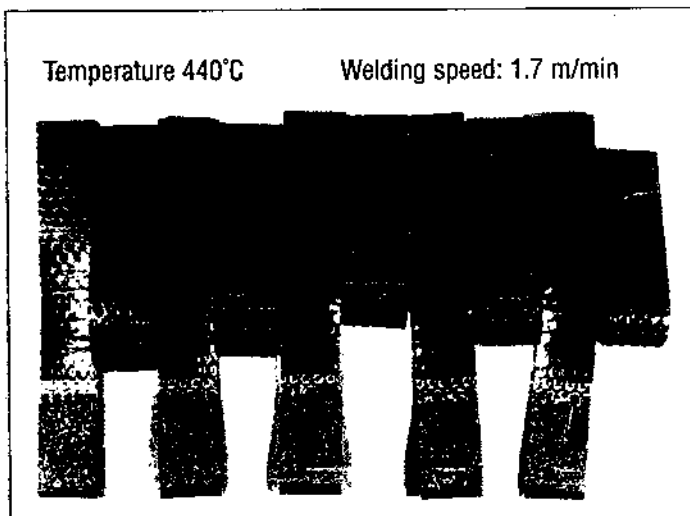


Figure 15. Fracture mode of welding joint.

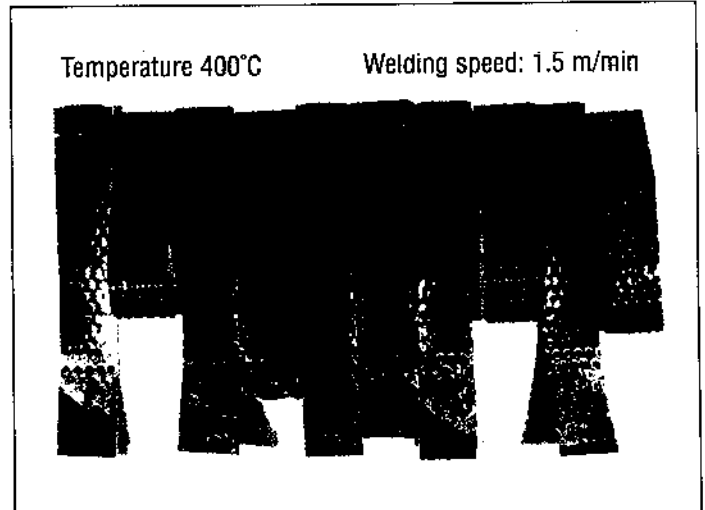


Figure 16. Fracture mode of welding joint.

gardens should have not only root resistance, but also high reliability of waterproofing; the quality of the welded seams is especially important. As a result of trial welding, it was found that test cuts of the welded seam are the most important measurement during inspection, even if the seam was welded with the appropriate welding conditions of hand welders and automatic welders.

Vacuum tests by a plastic box, inlet, or needle are also essential for the inspection of welding seams. Daily quality control of welding and vacuum testing is very important to certify the quality of welded seams. Trial welding before everyday work by every worker is useful for teaching the importance of airtightness of seams to workers who have had little experience with airtightness of welding. Airtightness provides watertightness.

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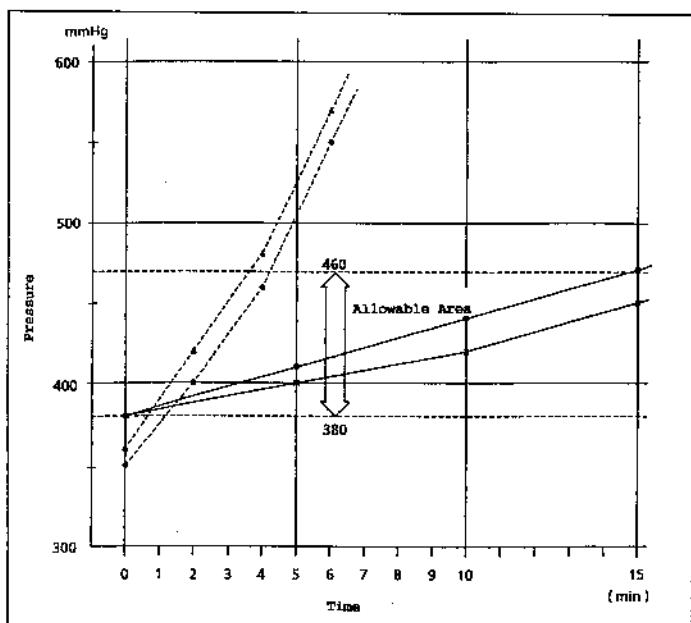


Figure 17. Pressure increase of vacuum test.