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Improving stopping construction to minimize leakage

Roy H. Grau III, **Andrew L. Mazzella**, and **Anu L. Martikainen**
Office of Mine Safety and Health Research (OMSHR), National Institute for Occupational Safety and Health (NIOSH) Pittsburgh

Abstract

The proper sealing of stoppings is an important step in reducing leakage from the intake to the return airways. Leakage and the subsequent loss of ventilation resulting from improperly sealed stoppings can lead to unhealthy and unsafe working conditions. The research presented in this paper investigates the total leakage of a stopping, including air leakage through the stopping, at the stopping perimeter, and through the coalbed. The study also examines sealing considerations for stoppings that are constructed under roof control screen, the effects that wooden wedges had on inhibiting efficient application of polyurethane foam sealant, and airflow leakage through the surrounding coal. The work involved building a stopping in a dead end room of the NIOSH Safety Research Coal Mine and then pressurising the room using compressed air. Stopping leakage was evaluated by measuring air pressure loss in the enclosed room due to the air leakage. Part of the research utilises a diluted soap solution that was applied to the stopping and the surrounding coal to detect air leakage signified by bubble formations. The results show that stopping leakage can be minimised with proper sealing

Introduction

Stoppings are the primary ventilation control system used by mine operators to course ventilation air through a mine. Since stoppings separate fresh intake air from the return air that may contain dust, contaminants, or potentially explosive methane mixtures, it is important to keep leakage to a minimum through stoppings to keep personnel both healthy and safe. The number of stoppings being constructed each year requires the mining industry to devote considerable resources and time for construction and maintenance of these structures. Knowledge of efficient stopping construction benefits all mineworkers.

Prior research concerning stopping leakage focused on stopping construction aspects such as block types, construction techniques, sealant products, and sealing methods. The tests included both laboratory and in-mine tests. Generally, laboratory studies included pressurising areas that were enclosed by a stopping built exclusively for testing. In-mine tests often simply averaged leakage rates from several stoppings because of the difficulty in determining the actual leakage from a single stopping in a working coal mine.

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The research presented in this report was conducted on one stopping that was built at the NIOSH Safety Research Coal Mine in Bruceton, PA. It differs from previous research in that the stopping was constructed underneath steel and fiber roof control screen, which is finding increasing application in underground mines to control minor falls of the roof. Two other areas the research investigated were the effects that wooden wedges had on inhibiting efficient application of polyurethane foam sealant and understanding airflow leakage through the surrounding coal. Understanding leakage quantities through the coalbed and through or around the stopping will help mine ventilation planners to better identify possible leakage paths and to quantify their flows for ventilation analyses. Since the tests involved sealing gaps in or around the stoppings, the information found is also transferrable to stoppings that are built underneath uneven roof.

Background

Some of the earliest work on stopping leakage was performed by Peascod and Keane (1955), who claimed that the air quantity losses through stoppings are greatest in the outby portion of the intake where there is the greatest pressure differential, accounting for about 75% of the total loss. Further stopping leakage research was performed by Holland and Skewes (1962), who found that the leakage through a mortared joint stopping was reduced 10-15% by applying a mortar or paint coating. A dual coating of mortar combined with paint reduced the leakage rate to 2-3% of the original rate by comparison to a stopping having no coating. These findings showed that a cement coat or painting significantly decreased leakage and that the stopping block material itself was secondary to coating in preventing leakage.

Further stopping research was performed by Kawenski et al. (1965), who pressure tested stoppings composed of blocks of slag, cinder, and gravel as well as polyurethane and mortar sealants. Similar to what Holland and Kewes (1962) determined, Kawenski found that the seal of the stopping to the ribs, roof, and floor - not the block type itself - was the most important variable in reducing leakage. However, it appears that minimal work in either research cited above addressed leakage at the perimeter of the stopping in real-life conditions.

Timko and Thimons (1983) evaluated various stopping construction methods to determine the best ways to reduce leakage. Their study found that the construction method significantly affected leakage and concluded that multiple layers of sealants, as well as sealants containing fiber (reinforced), increased air leakage resistance. Applying the sealant using a brush rather than a trowel resulted in less leakage. Reducing leakage around the perimeter of the stopping was best achieved by "keying" the stopping blocks into the ribs, top, and bottom of the entry.

Although leakage through stoppings was reduced by the above enhanced installation techniques, all stoppings leaked to various degrees. Timko and Thimons noted in their study that stopping leakage was reduced an average of 33% (25-36% range) after six months due to rock dust plugging small voids, but that leakage increased 40% after two years due to stopping damage from ground movement. Leakage rates exceeding 0.3 m^3/s (600 cfm) were found in new stoppings where loose rib rock was not removed before stopping construction.

Lastly, leakage was minimised where the corner interface of the stopping with the rib or roof was a smooth patchwork extending several inches from the stopping onto the rib, almost eliminating air leakage in the stopping perimeter.

Gandy (1998) measured the resistance across four stopping types in five ventilation surveys at continuous miner sections. He found stoppings that were covered with TYVEK ®, a blanket type material manufactured by Dupont, produced significant reductions in leakage.

Alternatives to block stoppings, such as those constructed of steel sheets, are available. Steel stoppings are generally assembled from prefabricated panels, which are pre-sized to the dimensions of the mine entry. Steel, or Kennedy stoppings, are advantageous because of quick assembly time and ease of material handling. Oswald et al. (2008) performed a study investigating and comparing the resistances of block stoppings and Kennedy stoppings. This research found that in all cases, the leakage resistances of block stoppings were higher than those of Kennedy stoppings. Furthermore, in stoppings of average condition, block stoppings had a 40% higher air resistance than Kennedy stoppings. However it should be noted that leakage through steel stoppings such as the Kennedy stopping can be reduced by sealing the joints using a tape suitable for that purpose. A study performed by Burke (2003) found that block size uniformity is crucial in creating a stable stopping, while blocks of non-uniform size promote stress concentrations in the stopping. These stresses can result in fracturing and failure of the stoppings with subsequent leakage. Batchler and Barczak (2008) and Oyler et al. (2001) found that horizontal foam strips laid between rows in concrete block stoppings, designed to yield under load, actually increased the stopping damage, with the yield strips promoting unequal loading, resulting in leakage cracks.

A final consideration for reducing leakage through stoppings is the condition of the ribs and roof, which includes the presence of roof control screening. Roof screening is becoming more common in coal mines to prevent falls of rock. Robertson and Hinshaw (2002) found that roof screen is effective in reducing falls of smaller rock from the immediate roof. No studies have been performed determining if roof screen hinders adequate sealing between the roof and the stopping. Certainly by observation, stoppings built under roof screening have the potential to increase air leakage.

Stopping construction

The prototype stopping was constructed in the NIOSH Safety Research Coal Mine in a dead-ended entry using materials and procedures commonly used in underground coal mines for stoppings as shown in Figure 1.

The stopping was built approximately 1.2 m (4 ft) from the end of the coal face, creating a small room that was enclosed by the stopping, the face of the mine, and the coal ribs. The entry dimensions were approximately 4.3 m (14 ft) wide × 2.0 m (6.5 ft) high. The stopping was constructed using Omega blocks, which is a low-density product 352 kg/m^3 (22 lbs/ft^3) composed of a mixture of Portland cement, fly ash, and other substances. The block dimensions are 0.61 m × 0.41 m × 0.2 m (24 in × 16 in × 8 in). These blocks were dry stacked with the 0.61-m × 0.41-m (24-in × 16-in) side down and the stopping was not keyed into the rib or floor. This arrangement is typical of that used in a coal mine as the larger base area increases the stopping's stability. The stopping was installed with a man-door that was set at a slight angle allowing it to automatically close due to gravity.

In order to simulate leakage and mine ventilation pressures, compressed air was injected into the enclosed room at varying rates until a maximum pressure of 1245 Pa (5 in WG) was reached inside the room. The pressure was measured using a Viatran pressure transducer, Model 2746CBCCH. The compressed air was measured using a Sip 200-DC24-Air Sage Prime thermal mass gas flow meter. A total of four tests were performed where a predetermined sealant application was applied on the stopping after each test. With the tests performed in this manner, it was possible to determine the impact each additional sealant application had on leakage.

Results

The first pressure-leakage test, Test 1, was performed without sealant applied to the stopping. As compressed air was introduced into the enclosed room, the numerous leakage paths prevented air pressure to develop. During subsequent pressure-leakage tests, the stopping was progressively sealed more thoroughly. In preparation for Test 2, B-Bond MS Mine Sealant was applied to the high-pressure side of the stopping and along the stopping perimeter. B-Bond Mine Sealant, manufactured by Quickrete, is a surface bonding cement containing a blend of Portland cement, fiberglass fibers, and special additives. After a drying period of four weeks, Test 2 was performed with the room being pressurised to 1245 Pa (5 in WG) with a flow of 0.472 m^3/sec (1,000 cfm). During pressurisation, the relationship between pressure and leakage was linear as shown in Figure 2. Leakages were easily detected by feeling the airflow with the hand and by sight using smoke from ventilation smoke tubes as shown in Figure 3. The leakage was located primarily at the top and sides of the stopping and around the man-door.

Preparation for the third pressure-leakage test (Test 3) included adding polyurethane foam sealant to the perimeter of the high-pressure side of the stopping as shown in Figure 4 and around the man-door. These improvements resulted in a leakage reduction of 62% to 0.177 m3/sec (375 cfm) at 1245 Pa (5 in WG). The pressure increase followed the relationship shown in Figure 2.

Although airflow leakage was significantly reduced during Test 3, leakage was still evident even though the stopping was sealed with polyurethane foam. Ventilation tube smoke released on the high-pressure side readily passed between the roof and foam, showing that the interface between the stopping and the roof provided minimal resistance to airflow leakage. Although the foam appeared to thoroughly seal the stopping perimeter, the foam was covering the stopping and roof control screen only superficially, which did not create an adequate seal. This test showed that there were two hindrances to effectual sealing of the stopping: the presence of roof control screen and the presence of wooden wedges that are typically used to keep the stopping in place. Both the roof control screen and the wooden wedges blocked the penetration of the polyurethane foam and prevented the foam from filling voids between the blocks and the roof or ribs. The wooden wedges were positioned in the normal manner with the wedges extended out past the plane of the stopping wall.

Nevertheless, the placement of the wedges in this manner prevented the foam from being sandwiched between the stopping block and the roof and allowed only a superficial foam coating.

Preparations for Test 4 consisted of removing the polyurethane foam at the roof perimeter by hand scraping and removing some of the wedges. The foam was then reapplied between the stopping block and the roof, rib, and roof control screen material. This foam application differed from the previous test in that, rather than superficially spraying the stopping, the wand applicator tip was inserted in any cracks or leakage paths, allowing the foam to flow from inside to outside the crack. The surface area of the low-pressure side of the stopping also was sealed with B-Bond. These changes produced a dramatic reduction in stopping leakage. Figure 2 shows the leakage function being nearly linear for Test 4. A pressure of 1245 Pa (5 in WG) pressure was achieved in the sealed room at a leak-age flow of 0.019 m^3/sec (40 cfm). This result was obviously more favourable than that for the first test, which had 0.472 m^3/sec (1,000 cfm) leakage at the same pressure.

In order to determine the benefit of sealing the stoppings and to relate the test results with those for other types of stoppings, resistance factors for the stoppings performed in Tests 2 to 4 are compared to those found by Oswald (2008) and are detailed in Figure 5. The chart shows varying resistance factors compared to stopping quality and provides ratings for Kennedy (steel) stoppings and concrete block stoppings on a scale of poor, average, and excellent based on observation criteria reported by Oswald. Stoppings rated in poor condition have several cracks that allow significant leakage and are in need of repair. Average stoppings are the most common stopping condition found in underground coal mines and would be stoppings that although not near perfect in both condition and construction, are adequate in their application in the mine. Stoppings in excellent condition have high air resistance and have minimal leakage; generally, these stoppings are those that have been coated with a sealant. The stopping assessed in Test 1 was not considered in this evaluation due to its high leakage quantity. The stopping in Test 2 fell into the poor category and had slightly lower resistance than both the block stopping and Kennedy stopping. The stopping in Test 3 fell into the average stopping category, as it had a resistance lower than the block stopping but higher than the Kennedy stopping. The stopping in Test 4 fell into the excellent category; and had a resistance nearly 50% greater than the block stopping with excellent condition, and 140% greater than the Kennedy stopping.

The results of the current stopping tests can also be compared with the results found by Timko and Thimons (1983) from stoppings assessed in underground coal mines. The authors found that a hollow core stopping that was brushed with reinforced mortar on one side and with the stopping keyed into the floor and rib gave excellent leakage results of 0.023 m^3/s (50 cfm) for 9.29 m^2 (100 sq ft) of stopping surface at 620 Pa (1 in WG). This was comparable with the best stopping in Test 4, which leaked 0.025 m^3/s (52 cfm) after normalising the test results to an equivalent size and pressure. This result is noteworthy because a stopping that is keyed into the rib and floor requires more time for construction than simply applying polyurethane foam.

Normalised leakages for the poor and average stoppings from Tests 2 and 3 were also compared to those values obtained by Timko and Thimons. Normalised leakages for the poor and average stoppings were 0.097 m^3/s (205 cfm) and 0.087 m^3/s (185 cfm), respectively. These values exceeded the 0.066 m^3/s (140 cfm) reported by Timko and Thimons for a new conventional hollow block stopping coated with mortar on one side. The poor and average stoppings leaked less than the 0.109 m^3/s (230 cfm) reported for the same stopping studied by Timko and Thimons after a two-year period. One significant difference between the test stopping and the Timko and Thimons stopping was that the test stopping had a door while the stopping studied by Timko and Thimons did not.

Soap solution bubbles test

Visual observation of leakage through stoppings gives a better understanding of leakage paths, particularly those through the strata surrounding the stopping. Also, smoke can be difficult to discern at low leakage quantities, as evidenced in Test 4. To further understand leakage pathways, after Test 4 was completed, the stopping was left intact and a watery soap mixture was sprayed onto the surrounding strata and on the low-pressure side of the stopping. As in the previous tests, compressed air was injected into the room. A photographic record was developed of bubbles being formed on the stopping's surface and surrounding strata. This was performed at pressures of 375 Pa, 750 Pa, and 1120 Pa (1.5 in, 3.0 in, and 4.5 in WG).

Bubbles started forming at the lowest pressure, 375 Pa (1.5 in WG), and as would be expected, bubble size, growth rate, and quantity increased with pressure. The bulk of the bubbles formed at the stopping perimeter, primarily at the roof, but also along both ribs. No leakage was observed at the floor. The access door, which was sealed with a rubber gasket and foam, leaked at all pressures. The air leakage through the coal rib appeared to be minimal, and bubbles were only present at 1120 Pa (4.5 in WG) and located about 0.3 m (1 ft) outby the stopping. At one point, a very small bubble appeared approximately 0.91 m (3 ft) outby the stopping on the right rib.

Stopping construction rules-of-thumb

This study has added to the knowledge developed through the years detailing the best stopping construction methods to minimise leakage. Combining past studies and the results from this study, rules-of-thumb that minimise leakage for constructing block stoppings and, where applicable, for steel stoppings are provided.

- Block type is much less important than the sealing method for preventing leakage.
- Remove broken weathered rib material before constructing the stopping and, if possible, key the stopping into the floor and ribs.
- Apply reinforced sealant on both high and low-pressure surface areas. The sealant is better applied using a brush rather than a trowel.
- Apply a reinforced mortar on the perimeter several inches onto the rib to form a cove between the stopping and the rib or roof.

- Past studies have shown that laying horizontal foam strips between rows in block stoppings may actually promote stopping damage by creating unequal loading of the stopping.

Apply polyurethane foam with the wand tip inserted into cracks rather than applying it superficially. Polyurethane foam can be effective in reducing leakage when the stopping is built under uneven roof.

Apply polyurethane foam before inserting wooden stability wedges in the stopping. Wedges should be inserted as the foam is drying.

Conclusions

These tests showed that using a normal visual inspection to determine the adequateness of a sealant or polyurethane foam at inhibiting air leakage through a stopping is unreliable. During these tests, a coal mine room was enclosed by a stopping that was sealed with B-Bond MS Mine Sealant and polyurethane foam. The polyurethane foam was applied in a spraying manner on the stopping and the room was pressurised using compressed air. Smoke from ventilation smoke tubes revealed many leakage paths around the foam.

Although these results are limited by the tests being performed at one location, with only a few scenarios including one brand of foam and sealant, the results do show some significant findings. The superficial application of the polyurethane foam provided poor sealing, particularly with highly irregular surfaces such as roof support screen material or where wooden wedges blocked the penetration of the foam. A subsequent test showed that a better approach was to apply the polyurethane foam by inserting the pressure wand in cracks or leakage paths as far as possible, applying the foam and then inserting the wedges while the foam was still wet.

A water-soap solution was used to visually detect air leakages. Based on this solution being sprayed on the stopping and coalbed, the air leakage through the coalbed was minimal compared to the leakage through or around the stopping. The test revealed only a couple of bubbles on the coalbed and only at the highest pressure of 1120 Pa (4.5 in WG). The soap bubble tests revealed that the stopping face leaked at random locations but most leakage occurred at the stopping perimeter. Leakage occurred at all pressures even though both sides of the stopping were coated with B-Bond Mine Sealant.

As would be expected, leakage differences increase significantly as pressures increase, and the differences in leakage between the best-sealed stopping and the other stoppings were significant. This would indicate that more diligent effort in stopping sealing is necessary where higher pressures are present.

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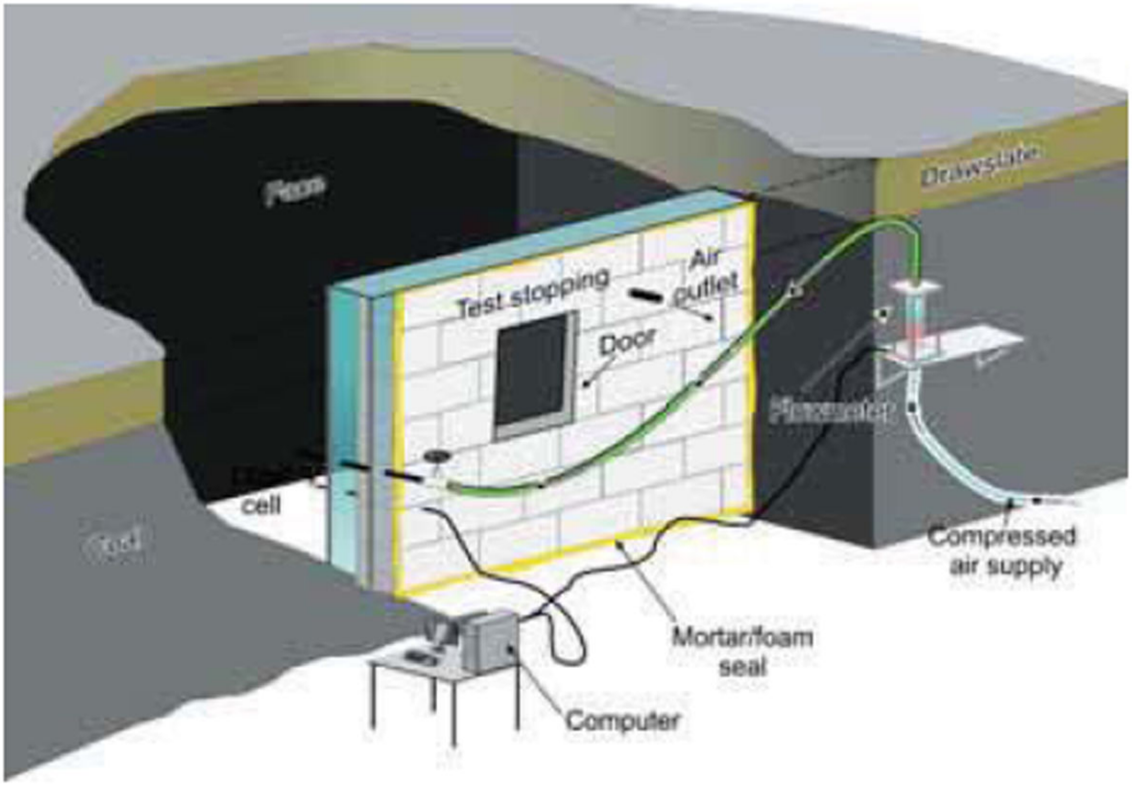

Figure 1.
Test setup

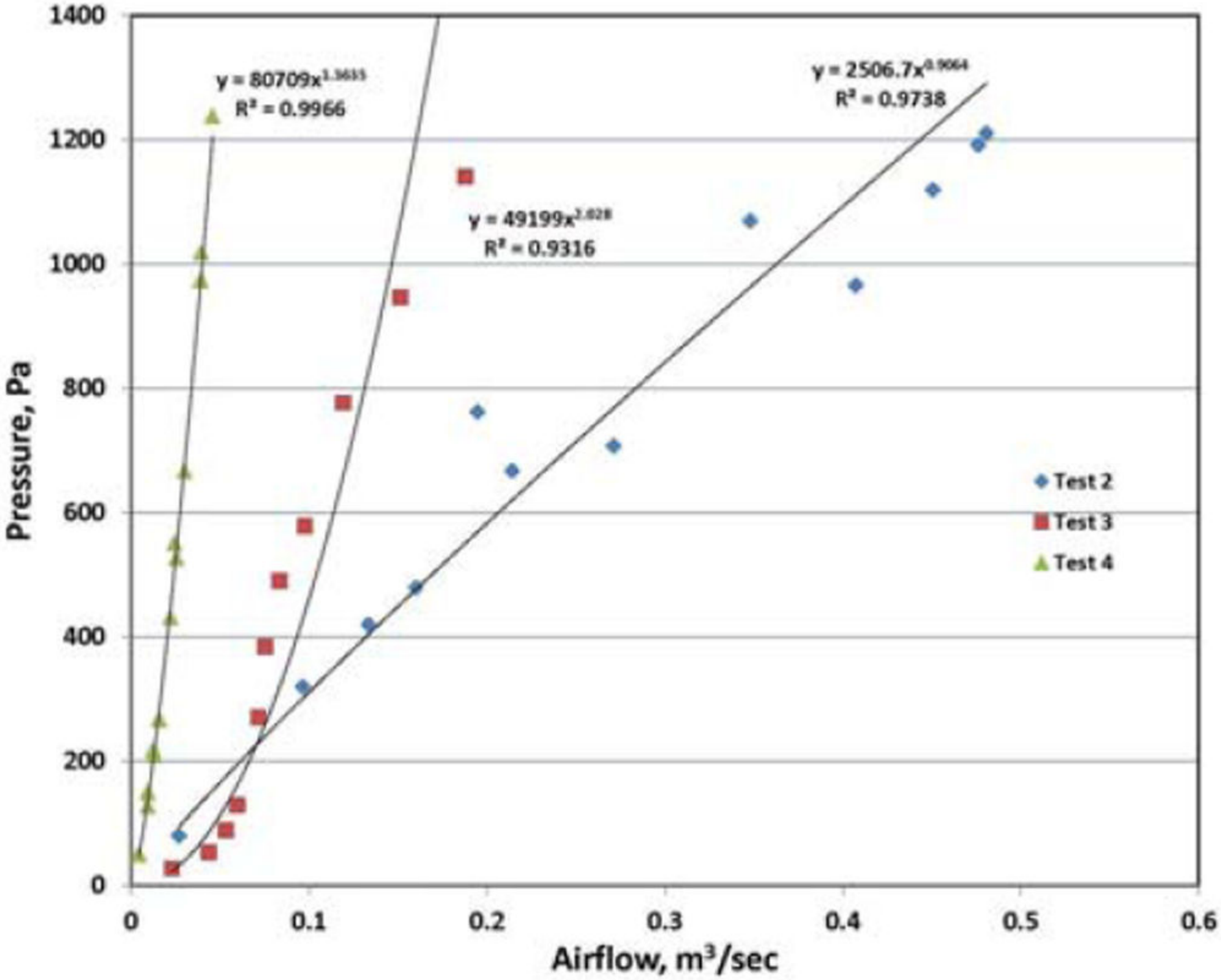

Figure 2.
Airflow leakage at different pressures for stoppings tested

Figure 3.
Smoke leaking through the stopping perimeter at the roof for Test 2

Figure 4.
Polyurethane foam sealing stopping at roof on pressurised stopping side for Test 3

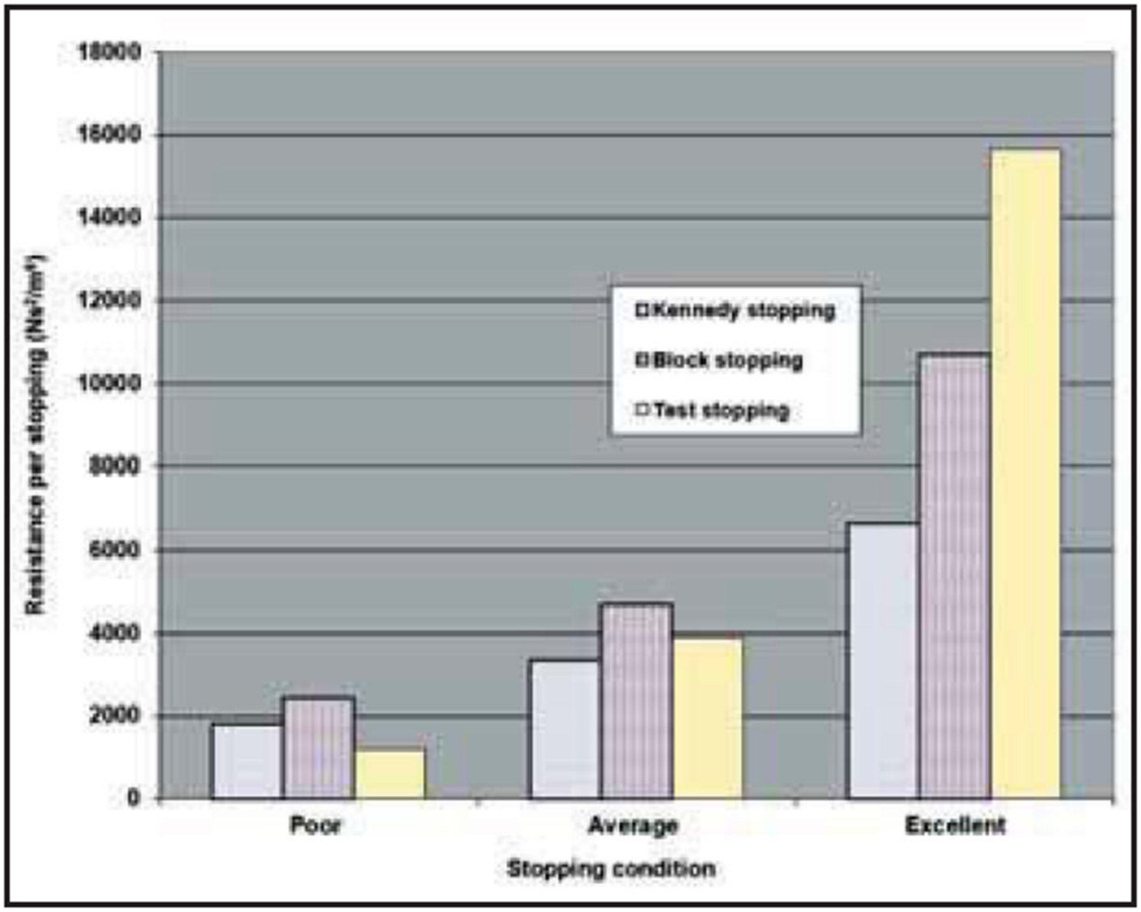

Figure 5.
Resistance factors for various stopping types

Figure 6.
Soap bubbles on stopping and at the right rib at 1245 Pa (4.5 in) WG