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Publisher's version / Version de l'éditeur:

ASTM Special Technical Publication, 790, pp. 65-77, 1982

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METHODS OF EVALUATING SINGLE-PLY ROOFING
MEMBRANES

H.O. Laaly

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ANALYZED

Reprinted from
Single-Ply Roofing Technology
American Society for Testing and Materials
Special Technical Publication 790, 1982
p. 65 - 77

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DBR Paper No. 1089
Division of Building Research

Price \$1.50

OTTAWA

NRCC 21088

Canada

3717680

H. O. Laaly¹

Methods of Evaluating Single-Ply Roofing Membranes

REFERENCE: Laaly, H. O., "Methods of Evaluating Single-Ply Roofing Membranes," *Single-Ply Roofing Technology*, ASTM STP 790, W. H. Gumpertz, Ed., American Society for Testing and Materials, 1982, pp. 65-77.

ABSTRACT: In the last 20 years several new types of roofing material have been introduced to the construction industry, including various inorganic and organic materials and their combination, generally prefabricated. This paper deals only with single-ply membranes made from such materials as flexible polyvinyl chloride (PVC), elastomers, that is, polyisobutylene (PIB), ethylene propylene diene monomer (EPDM), hypalon (CSPE), and other rubber and rubber-like materials and reinforced modified bitumens.

As there is need for criteria to facilitate appropriate selection and for specifications to ensure proper application, several test methods have been evaluated that assess physical, mechanical, and weathering properties of single-ply membranes. Some have been incorporated in the Standards of the Canadian General Standards Board (CGSB).

Some of the more important tests include those for lap-joint performance, dimensional stability, water absorption, stress-strain properties, low-temperature flexibility, static and dynamic puncturing, load-twist, and the so called wheelbarrow test.

KEY WORDS: roofing, membrane, hot applied rubberized asphalt, cold applied liquid membranes, elastomers, polyvinyl chloride, sheeting, prefabricated, modified bitumen reinforced single ply, performance criteria, lap joints, roofing test methods, roofing specification, roofing standards, wheelbarrow test

After a century's use of bituminous built-up roofing (BUR), why have so many new materials been introduced to the roofing industry within the past 10 to 20 years? Published literature in Europe and North America especially *Roofing, Siding and Insulation* [1],² reflects some of the reasons behind this trend. The organization of several international symposia on roofing technology by the National Bureau of Standards (NBS) and National Roofing Contractors Association (NRCA) in the United States [2] and two international symposia on roofs and roofing in Brighton, England [3,4] dealing with new materials are self explanatory.

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²The italic numbers in brackets refer to the list of references appended to this paper.

This paper will address these questions as well as describe what the Division of Building Research, National Research Council of Canada has contributed to shed light on the composition, classification, testing, and application of roofing materials. The Canadian government has experienced heavy losses as a result of roofing failures and 8 years ago decided to take a special interest in the matter. The close cooperation that developed during the past 8 years between the National Research Council and the Canadian General Standards Board (CGSB), Canada Mortgage and Housing Corporation (CMHC), Canadian Roofing Contractors Association (CRCA), and roofing material manufacturers resulted in this intensive research.

Research on roofing materials at the Division of Building Research, National Research Council of Canada has been divided into two categories: conventional materials (organic felt, built-up roofing membrane, and asphalt shingles) and new materials. This paper will deal only with new materials, although it can not attempt to cover all types of new and specialized roofing materials in detail; only the most common and widely used materials will be discussed.

Chemists have contributed a great deal to present comfort by developing new products, among them polymeric materials which are used for various fabrications. Polymers are made of thousands of simple organic molecules combined in large molecules, a process that can occur by polymerization, polyaddition, or as a result of a polycondensation reaction. They consist mainly of a few elements (for example, carbon, hydrogen, nitrogen, and sulfur) that can be built into a desired form, just like bricks are used in various building shapes and designs. It is the selection, combination, and reaction of monomers that results in thousands of different thermosetting, thermoplastic, elastomeric, viscoelastic, and plastomeric products; these can be processed by injection, molding, extrusion, vacuum forming, blow molding, calendering, etc.

Roofing technology has benefited greatly from advances in plastic and rubber technology, with the result that a large number of new roofing materials have been developed, among them the so called single-ply roofing membranes. With incorporation of polymeric and elastomeric materials, bitumen and coal-tar pitches are modified in a way that improves or upgrades their physical properties.

Classification

In an effort to develop a meaningful standard, roofing materials were divided into the following classes: (1) hot-applied rubberized asphalt (RA), (2) cold-applied liquid membranes (emulsion or solvent based), (3) prefabricated elastomeric sheeting (rubber and rubberlike materials), (4) flexible polyvinyl chloride (PVC) membranes, (5) prefabricated, reinforced, modified bituminous membranes, (6) rigid roofing panels, and (7) miscellaneous.

The advantages of the membranes (Classes 3 to 5) are that their thickness can be carefully controlled and that they are manufactured in a factory and application is rapid, inexpensive, and not dependent on weather. The disadvantage is that joints are required between adjacent strips. This does not occur with liquid-applied materials (Classes 1 and 2), but the difficulty with them is to ensure that the required thickness is produced over the entire roof area. In addition, cold or wet weather interferes with application, especially the cold-applied type.

Rubberized Asphalt (RA)

By blending reclaimed rubber powder (usually derived from old tires, cryogenic ground) and sometimes virgin rubber, asphalt, naphthenic oil, and mineral filler properly formulated and processed, a product is obtained that exhibits both viscoelastic and thermoplastic properties. It can be melted in a double-jacketed asphalt kettle and applied (with a squeegee) to the roof deck to form a monolithic membrane approximately 4 mm (150 mil) thick. Care must be taken to avoid prolonged overheating of RA in the kettle since this adversely affects the properties and performance of the RA membrane. It is used for roofing in protected or inverted systems and for waterproofing bridge decks and foundation walls. Using asphalt cutback as a primer prior to application improves its adhesion to the substrate.

It is reported [5] that some rubberized asphalts remain flexible at temperatures as low as -60°C (-75°F); straight asphalt, on the other hand, is brittle at 0°C (32°F). Crack-bridging properties of RA are very important. All the relevant requirements have been incorporated in CGSB Standard Hot Applied Rubberized Asphalt (37-GP-50M), including thickness, water absorption, and toughness. The latter is a measure that allows assessment of RA for cohesive and adhesive strength. The method was developed by Benson [6] in 1955 and was improved by the National Research Council (NRC) in 1977; molten RA is poured into a metal cup in which a special rounded bottom screw is positioned. After cooling, the screw is pulled out of the cup at a rate of 8.5 mm/s (20 in./min). The strip chart recorder shows a stress-strain curve indicating both energy requirement and elongation at break. This translates as toughness. The curves obtained, like electrocardiogram traces, can provide information about changes in formulation, manufacturing parameters, and other factors.

Cold-Applied Liquid Membranes

This group offers an advantage over hot-applied systems in that no kettle is required, and the product can be applied with a spray gun and squeegee for solvent-based materials or with a double-nozzled spray gun for emulsions, but the films need more time to dry or cure. The uncured, or freshly applied, emulsion type could be washed away by rain immediately after application,

and both types could be damaged by physical impact while still soft. In general, favorable weather conditions are a prerequisite of cold-applied liquid membranes. Curing time and water resistance of the membrane are, therefore, critical properties. Failure to use a primer with some of the cold-applied liquid membranes will spell disaster due to lack of adhesion, if they are subjected to traffic after application.

Minimum levels of physical and mechanical properties are specified in the relevant CGSB standards (Appendix A). Some manufacturers demonstrate the flexibility of their materials by pressing and twisting the membrane with their fingertips, but quantitative evaluation is hardly possible with this approach and the National Research Council (DBR/NRC) has developed a load-twist apparatus. The technique indicates that the higher the degree of return after twisting, the higher the rubber content. A minimum of 50 percent return is necessary if the material is to withstand heavy twisting from heel pressure on the membrane. This test pertains to cold-applied modified bitumen and elastomeric emulsions after the monolithic membrane has formed.

If the substrate for cold-applied liquid membranes (silicones or acrylic emulsions) is a sprayed polyurethane foam insulation, not only the quality of the membrane, but also the physical properties of the foam will play an important role, particularly for compressive strength, a key factor for a durable roofing system. Another requirement of a cold-applied membrane is that it should have adequate impact resistance. DBR/NRC has experimented with a 1 kg (2.2 lb) metal bar dropped from a certain height on a spot exactly 1 cm² (0.155 in.²). Wide-ranging effects have been recorded for different foams and coatings. While one was damaged by an induced impact from a height of only 50 mm (2 in.), another remained intact after an induced impact from a height of 635 mm (25 in.). Materials that may have the same appearance do not necessarily perform equally well. Depending on polyurethane (PU) density and chemical composition of the coating, various types of failure may take place.

Prefabricated Elastomeric Membrane (Rubber and Rubberlike Sheet)

It has been almost 10 years since ethylene propylene diene monomer (EPDM) was developed. This type of rubber can be used for roofing, waterproofing, and linings. It is extremely weather and ozone resistant. Polyisobutylene (PIB), hypalon (CSPE) which stands for chlorosulfonated polyethylene, chlorinated polyethylene (CPE), polyisochloroprene (neoprene), and butyl rubber are all included in the one group, although some are not really vulcanized, because their intended use and chemical nature are similar.

Elastomeric membranes are applied as for Classes 4 and 5, except in making lap joints, because heat or solvent welding can not be used. Consequently, a most important aspect of this group is its lap-joints performance. In order to overcome the weakness of EPDM lap joints, Westly [7] and his

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co-workers investigated the causes of failure and found that removal of talc powder and surface contaminants before application of an adhesion promoter will improve the lap-joint strength of EPDM substantially. Lap-joint strength can be evaluated in two ways: shear test or peel test. It is reported that the peel test gives more reproducible results.

Weathering of rubber-based membranes differs from that of vinyl materials because most rubbers, especially those containing conjugated double carbon (C=C) bonds, are attacked by ozone. Correlations between natural and accelerated weathering have been reported for many rubbers [8]. The same percent elongation at break after 11 years of outdoor exposure was obtained in a few days in an oven at 100 and 120°C (212 and 248°F).

Flexible Polyvinyl Chloride (PVC) Membrane

PVC, which is made of PVC resin, plasticizer, filler, and heat and ultraviolet stabilizers, has been used for more than 15 years. It is produced by coating, extrusion, or calendaring processes in both reinforced and nonreinforced form. Some nonreinforced PVC will shrink as much as 5 percent due to memory effect and internal stress induced by the calendaring process [9]. Solutions to this problem follow different lines. The material should undergo an annealing process, about 10 min at 90°C (194°F) to release the internal stress, resulting in shrinkage in the machine direction of the rolls and a slight expansion in the cross-machine direction.

When using nonreinforced PVC instead of the annealed type for loosely laid and ballasted roofing, it is advisable to fold the membrane inward about 0.3 m (1 ft) at the perimeter, then fold it back again 0.3 m (1 ft) towards the edge of the roof or parapet wall, thereby allowing the material to shrink stress free. For fully adhered applications this precaution is not necessary. The other solution is to choose glass fiber reinforced PVC, which has a shrinkage rate below 0.01 percent. CGSB Standard Roofing and Waterproofing Membrane, Sheet Applied Elastomeric (37-GP-54M) provides for both shrinkable and nonshrinkable PVC and deals with selection and design.

Shrinkage in PVC was originally assessed by a 1 week exposure in a hot air oven at 80°C (175°F), but owing to the range of glass transition temperature of PVC which is close to 90°C (195°F) a 15 min hot air oven at 90°C (195°F) has been found most suitable. This procedure can be used for both loosely laid and loaded specimens (CGSB Standard 37-GP-54M). The presence of ballast inhibits shrinkage to a certain degree.

PVC is relatively easy to apply and can be tailor-made to any roof shape, even covering vent pipes, or it can be used as flashing material. Lap joints of PVC membranes are made by solvent welding or hot-air gun welding. The latter method is more reliable, as confirmed by comparative 1 week immersion in boiling water of both types of PVC lap joints. Hand-held hot-air gun welding has now come into use, at first, semi-automatic and recently, fully

automatic. The quality is very satisfactory, with welding speeds ranging between 30 and 51 mm/s (6 and 10 ft/min). The variables are nozzle temperature and welding speed, but these are strictly controlled (programmed). Tensile strength of lap joints is double that of the single-ply membrane itself.

To assess the resistance of PVC membranes to falling tools or sharp objects a 60-deg steel-cone penetration was found convenient and has been adopted in the CGSB Standard. A 3 kg (6.6 lb) weight resting on the cone for 1 min should not cause penetration of the membrane. Many public buildings, universities, and industrial roofs have a PVC covering, and consumption is tending to increase.

Prefabricated, Reinforced, Modified Bituminous Membranes

This class of material offers a twofold advantage: uniform texture and automatic control of all variables (speed of production, degree of saturation, coatings and rate of mineral granule surfacing, thickness of the membrane, etc.) during the manufacturing process. Prefabricated, reinforced, modified bituminous membranes are the result of decades of research and development in various scientific disciplines: polymers, elastomers, plastomers, petroleum industry, and roofing technology combined. Lap-joint quality is a paramount requirement. Normal asphalt has been used sometimes as a binder for the lap joints or for fully adhered systems. By itself, this is not good practice because in cold weather the asphalt becomes brittle and failure occurs at the interface. Another aspect that needs emphasis is the use of asphalt that is compatible with the membrane, one having the right range of softening point.

These problems can be obviated by using a single, double, or multiple-nozzle propane torch that melts the back surface of the membrane, applied either manually or semi-automatically. Better uniformity and speed are obtained with the automatic method.

It is possible, after exposure of the membrane system to freeze-thaw cycles or erosion, that granules will be detached from the surface, exposing the membrane directly to the elements and reducing the service life of the system. Annual inspection and, if necessary, remedial action involving torching and incorporation of more granules is recommended. The important criteria for this system, including lap-joint performance requirements, are described in CGSB Standard Membrane, Modified Bituminous, Prefabricated, and Reinforced Roofing (37-GP-56M) (Appendix A).

Testing

As all classes of membranes tend to have more or less the same function, some tests pertain to all systems. Even the best membrane is of little use if

water enters the system as a result of lap-joint failure. That is why, in CGSB Standard 37-GP-56M, great emphasis has been placed on lap-joint evaluation. The tension test should be carried out immediately after preparation and should be repeated after a 5 day immersion in hot water at 50°C (122°F) and subsequent 10 freeze-thaw cycles. Lap joints should show a tensile strength at least 90 percent that of the membrane itself. Clearly, stiff standards are required to ensure protection from premature failure of roofing systems, with a safety factor included in most cases. By using a Weatherometer with ultraviolet radiation produced by carbon or xenon arcs and water spray device, any ratio of radiation and rainfall can be simulated in a very short time and in a controlled manner.

Because the membrane has to accommodate structural movement, this aspect should be considered in the selection process. Low-temperature flexibility is very important for winter application. Included in the test are the following variables: mandrel diameter, speed of bending, degree of bending, and testing temperature. In case there might be microcracking after the bending test, a water tightness test must be carried out. For this a pipe filled with water is placed over the crack. No water infiltration should take place through the membrane overnight.

Dimensional changes resulting from heat aging or water absorption can be readily assessed with a travelling microscope. As most membranes in this class are protected by mineral granules, these must be checked also for embedment. It has been established that 50 strokes with a loaded steel brush should yield no more than 1 g (0.035 oz) of removed granules.

There are two puncturing tests: static and dynamic. In static tests a 25 kg (55 lb) weight is placed on the surface of the membrane through an 11.4 mm (0.45 in.) diameter [1 cm² (0.155 in.²) cross section] metal rod for a specific length of time, usually in the range of 30 to 60 min. Dynamic tests are conducted to assess the effect of damage caused by a falling object. Experience has shown that a 1 kg (2.2 lb) weight falling from 254 to 508 mm (10 to 20 in.) could be suitable. In both static and dynamic puncturing tests the support used for the specimen was a laboratory rubber stopper with a Shore A hardness of 50 ± 1 at room temperature. The tests must be carried out at two different temperatures, room temperature and -10°C (14°F) are suitable.

As far as performance of new roofing materials in the Canadian climate is concerned, nearly 40 representatives of various classes of new products have been already exposed at NRC sites in two cities with different climatological conditions, Ottawa (Ontario) and Saskatoon (Saskatchewan), for observation and future evaluation. Following 5 year exposure in Ottawa some of the specimens have performed extremely well, but a few have shown surface erosion and lap-joint weakening. The results of this study will be published at a later date.

Seasonal and daily temperature fluctuations have an effect on expansion and contraction of single-ply roofing membranes. Laboratory tests with in-

frared lights (500 W) on a strip of specimen measuring 1 to 2 m (39 to 79 in.) in length have provided useful information about dimensional stability. The energy spectrum of the Weather-ometer lamp (carbon arc or xenon arc) with appropriate filters makes it possible to assess the action of solar energy at a given wavelength range and intensity on any particular chemical bond in combination with artificial rain.

Fire tests and evaluation of wind uplift must be carried out also on representative roof systems, not on the membrane alone. The history of wind velocity in a given area is an equally important consideration in design, but does not fall within the scope of this paper.

Another test apparatus, just recently developed at DBR/NRC, is the wheelbarrow test. The idea stemmed from the fact that new roofing materials are sometimes damaged by other trades during or immediately after application. The apparatus consists of a solid graduated turntable on which the membrane is mounted. A conventional wheelbarrow wheel is placed on the specimen and loaded to 50, 100, or 150 kg (110, 220, or 330 lb), using weight and leverage principles. The degree of turn and transmitted load are correlated with the behavior of the membrane. This varies from slight surface marking to severe damage and tearing, depending on the quality of the material (Appendix B).

Most of the tests are either incorporated in CGSB Standards 37-GP-50M to 37-GP-61 (Appendix A) or are being considered by the relevant technical committees. Although progress has been made, more work lies ahead.

Acknowledgment

The author would like to express his thanks to C. C. Barrett, G. A. O'Doherty, and R. L. Dubois for carrying out the experimental work.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is submitted with the approval of the director of the division.

APPENDIX A

Various CGSB Standards for New Roofing Materials, 1982

- 37-GP-50M Hot applied rubberized asphalt (published March 1978).
- 37-GP-51M Application of hot applied rubberized asphalt (published Sept. 1979).
- 37-GP-52M Roofing and waterproofing membrane, sheet applied, elastomeric (10th draft—Aug. 1982).
- 37-GP-53M Application of prefabricated elastomeric sheeting (2nd draft—May 1982).

- 37-GP-54M Roofing and waterproofing membrane, sheet applied, flexible, polyvinyl chloride (published Jan. 1979).
- 37-GP-55M Application of sheet applied, flexible, polyvinyl chloride roofing membrane (published Sept. 1979).
- 37-GP-56M Membrane, modified bituminous, prefabricated, and reinforced for roofing (published July 1980).
- 37-GP-57M Guidelines for the application of modified bituminous, prefabricated and reinforced, membrane for roofing (2nd draft—Sept. 1982).
- 37-GP-58M Membrane, elastomeric, cold-applied liquid for nonexposed use in roofing and waterproofing (7th draft—Oct. 1982).
- 37-GP-59M Membrane, elastomeric, cold-applied liquid for exposed use in roofing (nontraffic bearing) (2nd draft—July 1980).
- 37-GP-60M Cold-applied, liquid, elastomeric membrane for *exposed* traffic bearing areas (2nd Draft—Jan. 1982).
- 37-GP-61M Application of cold-applied liquid, elastomeric membranes (early stage).
- 37-GP-62M Membrane, elastomeric, cold-applied liquid for use in waterproofing (early stage).
- 37-GP-70M Prefabricated, reinforced, modified bituminous membrane for waterproofing (4th Draft—Aug. 1982).

APPENDIX B

Wheel Barrow Test for Roofing Membranes

This test is intended to evaluate the vulnerability of roofing membranes to damage caused by workers during or after roofing application.

The apparatus consists of a 203 mm (8 in.) diameter, 101 mm (4 in.) wide, commercially-available wheelbarrow tire inflated to 24.1 kPa (35 psi). The load on the wheel can be varied from 200 to 50 kg (440 to 110 lb) by changing the weight or the position of the hanging weight on the leverage arm (Fig. 1).

Procedure

1. Calibrate the apparatus by changing the weight or leverage length to impose various weights on the wheel. Bathroom scales have been found suitable for this purpose, providing they have been tested for accuracy. Determine the combinations of weight and length required to produce loads of 150, 100, and 50 kg (330, 220, and 110 lb) on the wheel.

2. Cut from the membrane a representative piece, approximately 1540 cm² (1 ft²), and punch out five circular holes 6 mm (¼ in.) diameter using the round holding frame as a template.

FIG. 1—National Research Council (NRC) wheelbarrow test apparatus for the evaluation of new roofing materials, general view of the apparatus.

3. Place the specimen on the graduated turntable, put the round holding frame on the specimen, and align the holes. Tightly secure the specimen, using the five nuts and bolts. Position the plate at 0 or 180 deg, depending upon the location of the scale.

4. Lower the unloaded wheel on the specimen. Exert a load of 150 kg (330 lb) and turn the table 90 deg in 2 s. Examine the membrane for signs of damage.

5. If the material is not damaged or shows only slight surface abrasion, turn the table another 90 deg in 2 s. If the membrane is damaged by the load of 150 kg (330 lb) turned through 90 deg, repeat the test on another location or specimen with a load of 100 kg (220 lb) turned through 90 deg. If there is no damage, complete the turn to 180 deg; if there is damage, reduce the load to 50 kg (110 lb) and repeat.

6. Report the combination of greatest load and turn at which damage does not take place, using the following scale

A1	150 kg (330 lb) load	180 deg turn
A2	150 kg (330 lb) load	90 deg turn
B1	100 kg (220 lb) load	180 deg turn
B2	100 kg (220 lb) load	90 deg turn
C1	50 kg (110 lb) load	180 deg turn
C2	50 kg (110 lb) load	90 deg turn

where C2 and A1 are the lowest and highest values, respectively, in this grading.

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DISCUSSION

*D. E. Richards*¹ (written discussion)—(1) What is test temperature(s) for wheel twist test?

(2) Have any tests been done at high temperatures such as 60°C (140°F)? (wheel twist test)

(3) have any tests been done at low temperatures such as -18°C (0°F)? (wheel twist test)

(4) What is base material over which membrane is placed during test? (wheel twist test)

(5) Have any criteria been established? (wheel twist test)

(6) Puncture test—what temperature at time of test? High? Low? What surface(s) (materials) are used under membrane?

(7) Point test—what temperature at time of test? High? Low? What base material(s) beneath membrane?

H. O. Laaly (author's closure)—(1), (2), and (3) The wheel twist test was conducted at room temperature, but it could be performed at higher or lower temperatures as well.

(4) The base material could be concrete, wood, insulation board, etc., but for the sake of uniformity and reproducibility a steel plate was used as substrate. It is possible also to adhere the membrane to the substrate using the same technique as is used in the actual roofing and waterproofing practice.

(5) It is well understood that the performance criterion is based on the severity of abuse and traffic characteristics, such as load and degree of

¹Owens-Corning Fiberglas Corporation, Toledo, Ohio 43659.

twisting. The rating, A1, A2, B1, B2, C1, and C2, quantifies the degree of success of material to traffic abuse, whereby A1 is the highest, and C2 is the lowest in the grading. Depending on expected traffic load, one can increase the performance criteria. I would not use a material that does not pass C2 on my roof!

(6) Static and dynamic puncturing tests were conducted at room temperature $-10 \pm 1^\circ\text{C}$ ($14 \pm 2^\circ\text{F}$). In general, the lower the temperature the more brittle the membranes. As substrate under the membrane, expanded polystyrene, wood, concrete, and rubber stopper were tried. The latter gave the best results.

(7) The cone penetration was conducted using a 60-deg machine-steel cone and a 1.0-mm (0.04-in.) thick aluminum plate as substrate. The main reason for this choice was hardness and electrical conductivity, which causes a short circuit and, in turn, stops the compression on the apparatus as soon as the membrane is punctured. For more details please read CGSB Standard 37-GP-54M (Appendix A).

*J. G. Smith (written discussion)*²—Could you please provide the supporting chemical reasoning as to why EPDM is so resistant to ozone?

H. O. Laaly (author's closure)—Ethylene $\text{H}_2\text{C} = \text{CH}_2$ and propylene $\text{CH}_3\text{-CH} = \text{CH}_2$ could be copolymerized according to Ziegler-Natta polymerization mechanism in which a transition metal halide, in association with an organometallic reducing agent such as aluminum alkyl, is specific. The structure of the obtained ethylene/propylene rubber

is very similar to natural rubber

called isoprene. As is known, oxygen and ozone react easily with the $\text{C} = \text{C}$ portion of natural rubber, especially at elevated temperature and stretched condition. The reaction of ozone (O_3) occurs over several stages, ending in an ozonide, which is an electrophilic additional reaction.

²Tremco, Ltd., Toronto, Ontario, Canada.

EPDM, which stands for ethylene, propylene, diene monomer, is obtained by reaction between a diene molecule

with EPR

In practice, various types of diene are used. EPDM is ozone resistant because the $\text{C} = \text{C}$ is significantly eliminated by a chemical reaction. For further information please read: (1) *The Chemistry and Physics of Rubberlike Substance*, L. Bateman, Ed., New York, Wiley, 1963 and (2) Morton, M., *Rubber Technology*, Von Nostrand Reinhold, New York, 1973.