

# STONE BALLAST DESIGN CRITERIA ON LOOSE-LAID SINGLE-PLY BALLASTED ROOFS FOR WIND SPEED, SIZE AND WEIGHT

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## ABSTRACT

Stone ballast on single-ply membranes is examined from the viewpoint of actual field performance. This data, combined with full scale wind tests and wind tunnel research, leads to design criteria for loose-laid stone on single-ply loose-laid membranes. Commercially available stone for all types of roofs is examined. Current gradation standards are found to contain large percentages smaller than 25mm (1 inch). The work demonstrates that full coverage is required and that current ballast is insufficient for high wind designs. High winds create an environment in which the current fines fraction will become airborne missiles. The final design criteria suggested develops minimum stone diameters for given rooftop wind speeds, and specific rates of application that will meet most situations for wind speeds ranging from 31 to 58 m/s (70 to 130 mph). Suggested stone sizes range from 19 to 108mm (¾ to 4¼ inches) in diameter applied at rates from 42 to 240 kg/m<sup>2</sup> (8.7 to 49 psf).

## SYMBOLS

- $C_p$  Coefficient of pressure (dimensionless)  
 $D$  Stone Diameter (mm) (in.)  
 $D_m$  Mean Diameter of Stone Mixture (mm) (in.)  
 $g$  Gravitational Acceleration (m/s<sup>2</sup>) (ft./s<sup>2</sup>)  
 $H$  Height Above Ground Level (m) (ft.)  
 $m$  An Exponent That is a Function of Ground Terrain (with a median value of ½)  
 $\Delta p$  Differential Pressure Between Inside and Outside Fiber of Membrane (Pa) (psf)  
 $V_h$  Wind Speed at Variable Height Above Ground (m/s) (mph)  
 $V_R$  Rooftop Wind Speed (m/s) (mph)  
 $V_{10}$  Standard Measured Wind Speed at 10m (m/s) (mph)  
 $W$  Application Rate of Stone (kg/m<sup>2</sup>) (psf)  
 $\gamma_s$  Specific Gravity of Stone  
 $\rho$  Air Density (kg/m<sup>3</sup>) (pcf)

The single-ply loose-laid roof system consists of three basic materials—single-ply membrane, insulation and ballast—all loosely placed on a structural deck in one of the two different configurations shown in Figure 1.

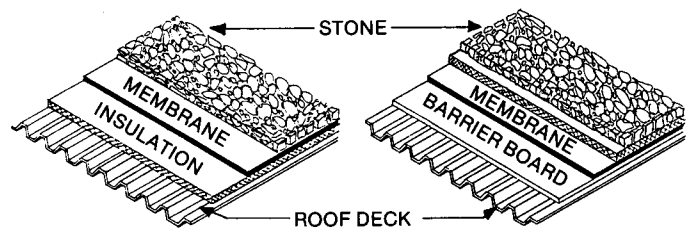


Figure 1

Single-ply membranes consist of numerous materials such as EPDM, Hypalon, neoprene, PVC and other organic sheets. The most elastic of these membranes is the EPDM sheet. Phalen<sup>1</sup> has demonstrated that most 45-mil commercial EPDM membranes can be identified by stress strain characteristics shown in Figure 2.

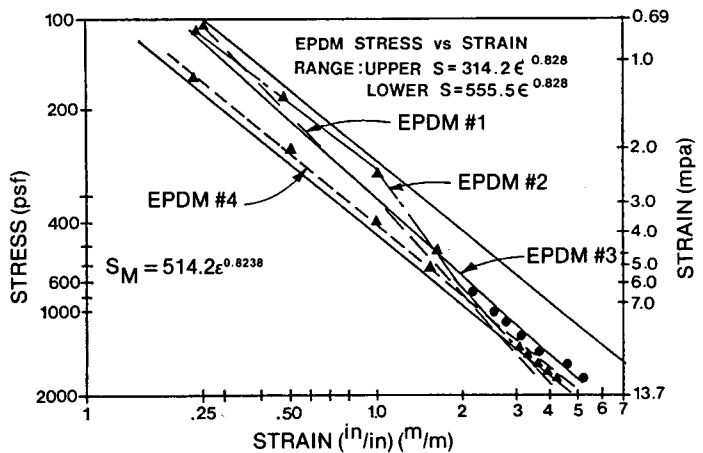


Figure 2

Stress strain characteristics indicate that this class of material exhibits a large initial deformation corresponding to a relatively small stress. Other membranes follow this type of relationship to a lesser or greater degree even when reinforced with fiber. Thus, essentially most single-ply membranes are relatively pliable and elastic at ambient conditions.

Doherty and Shloss<sup>2</sup> examined the influence of tempera-

ture and ultraviolet rays from sun light in long term-aging studies ranging from five to 20 years under natural conditions. Their data indicate that tensile properties decrease, that percent elongation decreases from 34 to 75 percent of its original value, and that hardness increases. These tests on EPDM, neoprene and Hypalon membranes clearly indicate a loss in strength and elasticity when subjected to elevated temperature and natural ultraviolet radiation. Phalen<sup>3</sup> subjected 12 commercial EPDM membranes to accelerated aging tests in accordance with ASTM aging procedures. His data shows the same general trend: brittleness and loss of elasticity. This indicates that if the membrane is protected, these effects would be reduced, thus enhancing membrane life.

SPRI<sup>4</sup> and Phalen<sup>3</sup> independently developed the basic design functions that stone ballast should perform on a single-ply membrane. These functions protect the membrane from:

1. wind uplift
2. puncture by humans, animals and naturally occurring events
3. temperature increases from sunlight
4. ultraviolet radiation
5. external fire hazards.

The previous data clearly indicate that to protect and substantially enhance membrane life, the loose-laid membrane must be *fully covered* by whatever ballast system is used.

Dove<sup>6</sup> forecasts the single-ply and BUR roof systems market through 1987 as shown in Table 1.

Type of roofing	Millions m <sup>2</sup>	Millions of sq. ft.
Total roofing area	739	(7950)
Total single-ply	334	(3600)
Total ballasted single-ply	150	(1550)
Total BUR	405	(4350)

These statistics indicate that the total amount of new stone and gravel that will be required in the United States from 1984 to 1987 will be as shown in Table 2.

Table 1 Total projected roofing market (3 years to 1987)

Item	Millions of tons	(Kg x 10 <sup>6</sup> )
Single-ply	28.0	(25400)
BUR	8.7	(7900)
Total	36.7	(33300)

Table 2 Stone requirements (3 years to 1987)

Current standards indicate that stone ballast consists of graded stone designated as 19 to 38mm (¾ to 1½-inches) at the minimum rate of 48.9 Kg/m<sup>2</sup> (10 psf). This type of ballast has been applied to numerous roofs throughout the United States and has resulted in the types of ballast failures shown in Figures 3, 4, 5 and 6.

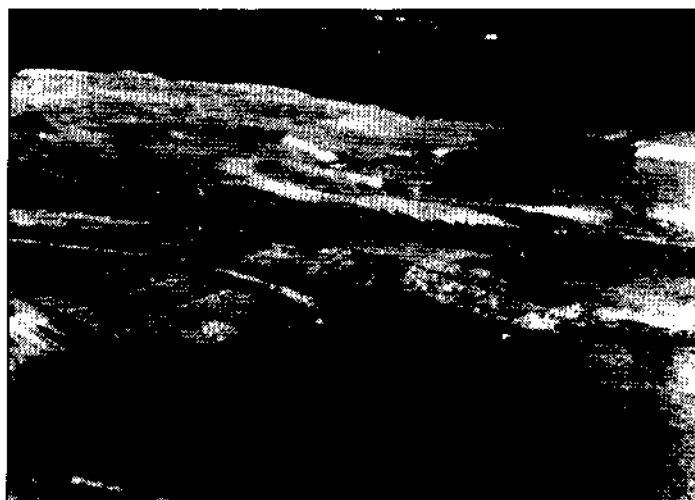


Figure 3 Roof in Houston, Texas after Hurricane Alicia

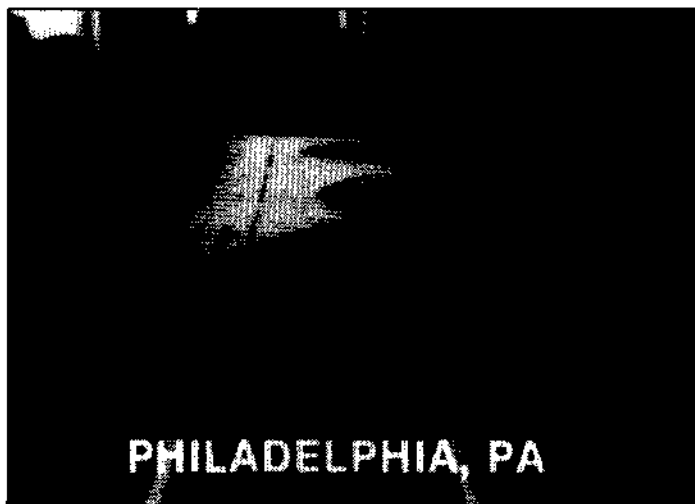


Figure 4 Ballasted single-ply membrane in Philadelphia, Pennsylvania

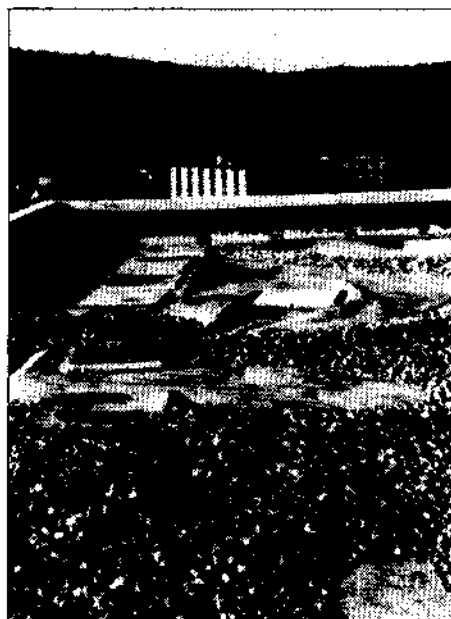


Figure 5 Single-ply roof system in Braintree, Massachusetts

Measurements from the full scale wind tests have identified the differential pressure and wind speed at rooftop level ( $V_R$ ) at which scour occurs. The differential pressure at which active scour<sup>5</sup> takes place was found to be related to stone diameter as shown in Equation 2A and 2B.

$$\Delta p = 3.12 + 7.176D \text{ (psf) where } D \text{ is in inches} \quad (2A)$$

$$\Delta p = 149.4 + 13.53D \text{ (Pa) where } D \text{ is in mm} \quad (2B)$$

These experimental results are compared to the theoretical results in Figure 9 and indicate excellent correlation of empirical and theoretical data.<sup>5</sup>

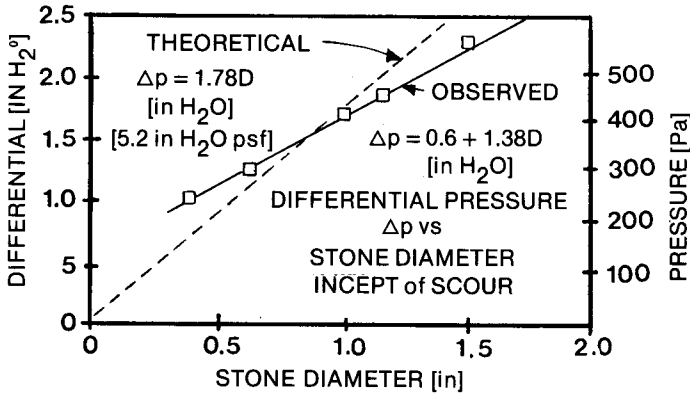


Figure 9

Results of full-scale wind tests relative to the rooftop wind speed ( $V_R$ ) at which active scour occurs yielded the following relationship:

$$V_R = 83.2D^{0.314} \text{ (mph) where } D \text{ is in inches} \quad (3A)$$

$$V_R = 13.47D^{0.314} \text{ (m/s) where } D \text{ is in mm} \quad (3B)$$

Results of the rooftop wind speed ( $V_R$ ) as developed in wind tunnel tests by Kind and Wardlaw<sup>17,18</sup> yielded median results that are somewhat lower. These results were developed for a solid deck without an elastic membrane, so they do not represent the membrane's influence. With no membrane present the small deviation should be anticipated. These results, shown in Figure 10, indicate good correlation with wind tunnel tests yielding slightly lower results but can be used as limiting criteria for preventing active stone scour.

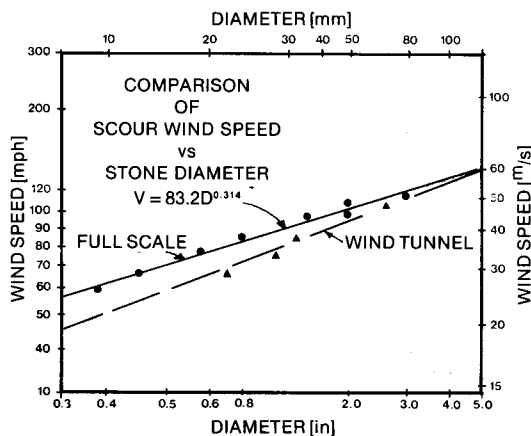


Figure 10

The coefficient of pressure is defined as:

$$C_p = \frac{\Delta p \cdot 2g}{\rho V_R^2} \quad (4)$$

By substituting equations 2A and 3A for  $\Delta p$  and  $V_R$  respectively into Equation 4 we find that the coefficient of pressure as a function of stone diameter in inches is:

$$C_p = \frac{(0.0135 + 0.031D)}{\rho D^{0.628}} \quad (5)$$

Using Equation 5 to obtain the minimum coefficient of pressure yields a critical stone diameter of 18.6mm (0.733 inch), and a minimum or critical coefficient of pressure of 0.59.<sup>(3)</sup> These results are depicted in Figure 11 where the coefficient of pressure is expressed as a function of stone diameter.

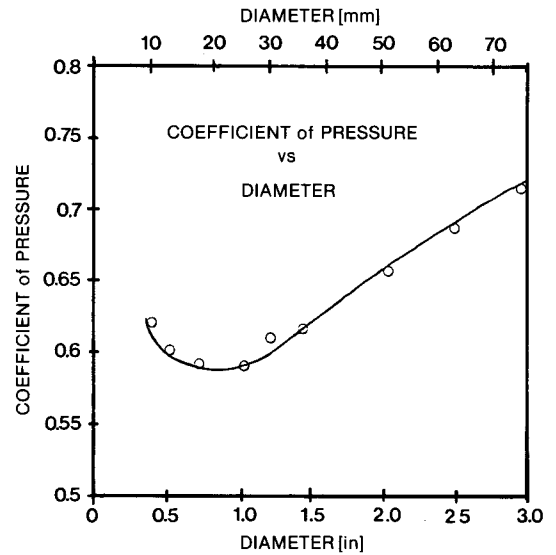


Figure 11

These results indicate that the coefficient of pressure for stone on single-ply membranes has a critical value of 0.6. Above that, active scour is a potential problem. This also indicates that stones with a diameter of about 18mm (¾ inch or less) are the most susceptible to scour.

Full-scale test results also have clearly indicated that a stone with a diameter of 19.1mm (¾ inch) appeared to be more susceptible to scouring. This observation is supported by the results shown in Figure 9. Figure 12 represents active scour and stone movement for 18mm to 25mm stone (¾ to 1 inch) at 36m/s (80mph). It indicates that the 18 to 25mm (¾ to 1 inch) stone fraction is most susceptible to scour and should not be used if at all possible.



Figure 6 Corner of single-ply roof membrane, Boston, Mass.

The reported scour failures, when combined with the large demand for ballast, obviously creates a situation in which the designer of the ballast system must understand the design criteria of stone ballast to accomplish *full coverage* on single-ply loose-laid membranes and to resist the effects of high wind speeds.

### WIND SPEED CONSIDERATIONS

Before examining design criteria for wind speed on stone ballast, a brief consideration of the design wind speed is essential. Governmental reporting agencies measure wind speed 10 meters (33 ft.) above ground level in an area where the wind is unobstructed. Davenport<sup>7</sup> has demonstrated that the wind speed varies as a function of height according to a power equation

$$V_h = V_{10}(0.1H)^m \quad (1)$$

where the exponent  $m$  is a function of ground roughness with a median value of about  $\frac{1}{2}$ .

ANSI<sup>8</sup> has organized basic wind speed data ( $V_{10}$ ) and has depicted them in contour maps to establish 50- and 100-year minimum design criteria. These values have been incorporated into building codes throughout the United States. The 100-year criteria indicates that minimum design wind speed ranges nationally from 31 to 58 m/s (70 to 130 mph) with an apparent median value of about 40 m/s (90 mph) for most of the United States.

Stiegler and Fujita<sup>9</sup> report that wind speeds from Hurricane Alicia ranged from 33.5 to 70.2 m/s (75 to 157 mph). Phalen<sup>10</sup> indicates that actual winds of 35 m/s (78 mph) occur with a frequency of once every 12 years in Massachusetts. Mazzagatti, Landers, and Walker<sup>11</sup> identify wind speeds ranging from 45 to 58 m/s (100 to 130 mph) in large areas of Florida. These references indicate that actual wind speeds exceed the ANSI wind speed criteria in many localities. All of these statistics suggest that the ground wind speed ( $V_{10}$ ) for design of rooftop gravel lies between 31 to 58 m/s (70 to 130 mph) depending on the location in the United States. From Equation 1 it is obvious that rooftop wind speed will exceed the ground speed for all structures in ex-

cess of 10m (33 feet) and will range from 36 m/s to well over 54 m/s (80 to 120 mph). Thus, rooftop wind speeds for stone ballast design purposes should range from 36 m/s to over 54 m/s (80 to 120 mph).

### BASIC PHENOMENA RELATED TO SCOUR OF ROOFTOP STONE

Full scale wind tests conducted by Phalen<sup>5</sup> developed, through actual observations, the basic phenomena to explain the scour mechanism of stone ballast on a single-ply, loose-laid membrane. The membrane that is unsupported between adjacent stones begins to balloon and pulsate due to the differential pressure created by the wind action over the roof's surface. As wind speed increases, elastic membrane pulsation is visible in the area of the highest local differential pressure with no stone movement. Then, as wind speed increases, ballooning and pulsation increase, creating a horizontal thrust on the stones, opening a small circular hole in the layer of ballast as shown in Figure 7. At this point scour has not yet occurred.

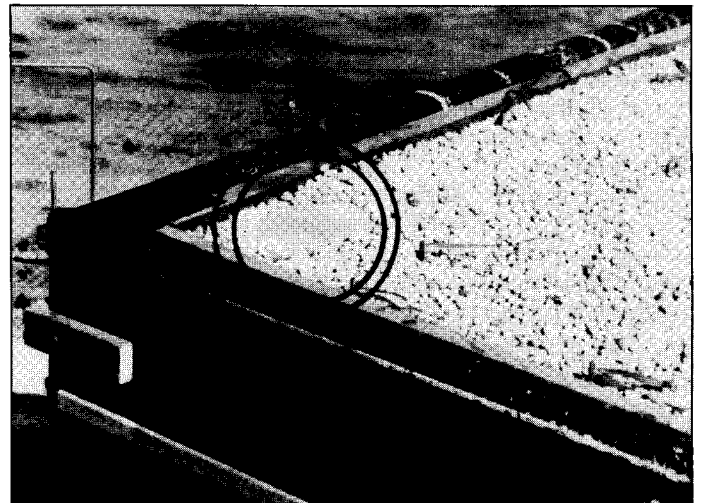


Figure 7

As wind speed continues to increase the differential pressure increases, accelerating the ballooning and pulsation thereby opening a large semi-circular hole in the ballast. At some point the differential pressure creates unstable stones that begin to blow along the roof's surface. Thus, the point of active scour is defined by a critical pressure and a wind speed of rooftop level ( $V_R$ ). This unstable condition is depicted in Figure 8.

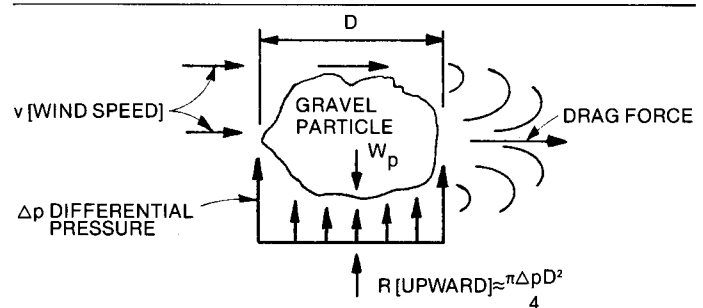


Figure 8

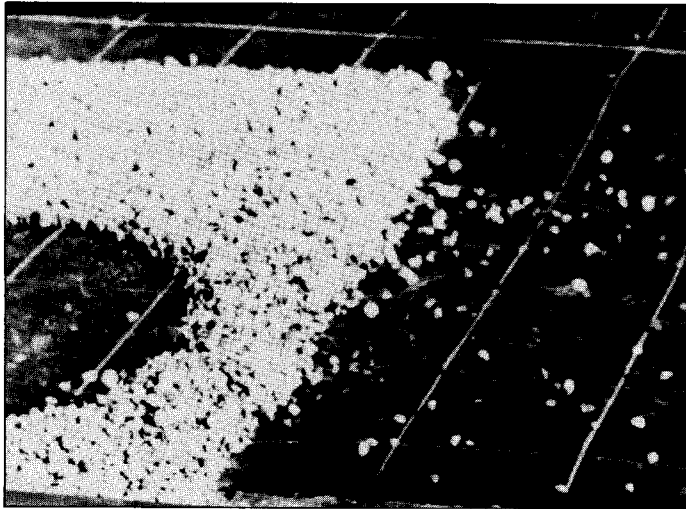


Figure 12

### VARIATION OF COEFFICIENT OF PRESSURE ON FLAT ROOFS

Fujita and Stiegler<sup>9</sup> have indicated that hurricane winds come from every direction of the compass rose (0 to 360 degrees), even though the storm center may travel in a very definite direction. Numerous investigators<sup>5,10,12,16,17</sup> have also shown that the worst case occurs when the wind impinges at an angle of 45 degrees (Beta angle) to the building face. (Figure 13.) Field observations indicate the same effects. (Figure 6.)

The earliest complete work relative to the magnitude and distribution of the coefficient of pressure as a function of the  $\beta$  angle was completed by Chien et al.<sup>12</sup> (Figure 13.)

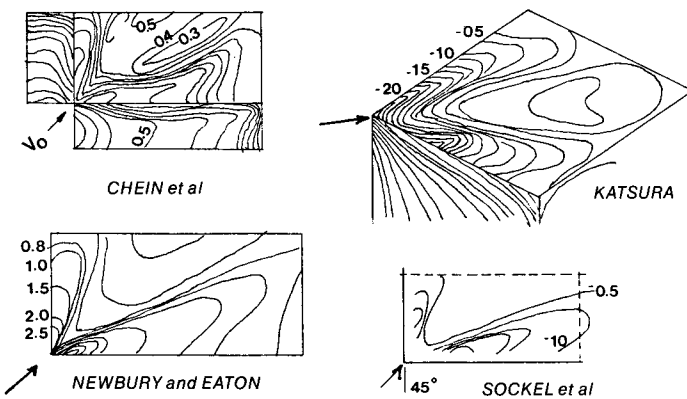


Figure 13

Considering that wind can come in at any corner of a structure, when we outline the  $C_p$  contours of 0.6 and 1.0 (the critical zones for stone scour beyond which active scour commences on Figure 13) it becomes apparent that in high wind areas a large portion of the roof will be subject to potential scour. Figure 14 shows the field of a roof that has scoured at the edges and is devoid of smaller stones. Thus, it is apparent from theory and field experience that, for a given wind, a minimum stone diameter is required to maintain the integrity of the membrane. Otherwise the type of scour shown in Figure 3 will take place.

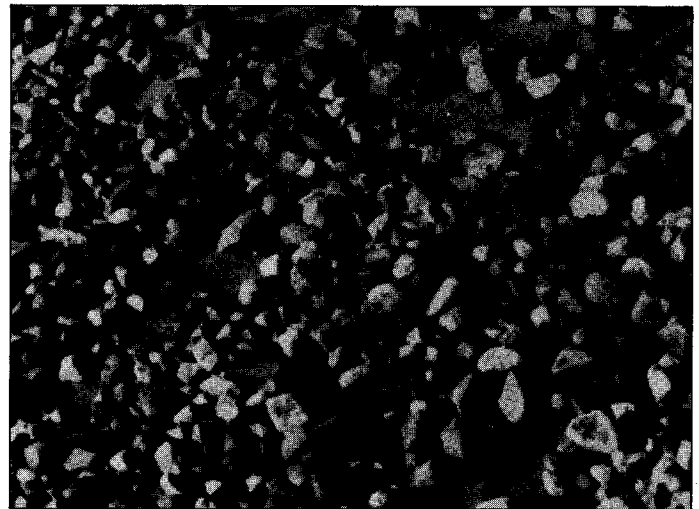


Figure 14

### PARAPET CONDITIONS

Numerous investigators have demonstrated that parapets reduce the maximum coefficient of pressure. Phalen<sup>13</sup> has demonstrated that even though the maximum  $C_p$  decreases, the  $C_p$  distribution over a given area is actually larger without a parapet. This moves the locus of the maximum coefficient of pressure further into the roof and actually increases the area of potential stone scour, because the critical coefficient of pressure (0.6 to 1.0) has been distributed over a larger area. Parapets retain some of the stone on the roof, but in piles which increase the local dead load. On roofs in which active scour can occur, major structural considerations must be made to eliminate overloading from stone scour.

### AIRBORNE STONE

The results of Hurricane Alicia demonstrated the effects of airborne stone on glass buildings in Houston, Texas. Minor<sup>14,16</sup> has demonstrated that the minimum speed required to break various types of glass is about 18 m/s (41 mph). This was one of the primary factors leading to about \$7 million of glass damage in Houston during Hurricane Alicia. Kind<sup>17</sup> has shown that stone of comparable size to that on BUR roofs (9.5mm or 3/8 inch) is dislodged from loose-laid stone ballast at 28 m/s (63 mph). Phalen<sup>15</sup> has shown that, under full-scale wind tests, 9.5mm stone (3/8 inch) actively scours at wind speeds under 27 m/s (60 mph). This clearly suggests that stone particles below a 3/4-inch size are extremely likely to fly off a roof and become destructive airborne missiles. They should be eliminated from consideration as roofing ballast.

### CURRENT STONE USED IN THE UNITED STATES

Various segments of the industry have indicated that current stone sizes being installed as ballast at the rate of 10 psf are adequate to satisfy the ballast criteria on single-ply roof systems. This prompted research activity at Northeastern University. Phalen<sup>3</sup> examined numerous samples of stone ballast obtained from commercial sources throughout the United States and determined their physical properties.

These properties are summarized in Table 3. Of 24 samples examined only one sample met the ASTM #4 stone criteria. All of the others did not.

Item	(in.)	(mm)	Lowest	Median	Highest
% Retained	2	(51)	0	0	0
% Retained	1½	(38)	0	2.96	9.7
% Retained	1	(25)	8.10	38.60	62.6
% Retained	¾	(19)	31.20	37.50	16.9
% Retained	½	(13)	52.70	18.90	7.3
% Retained	⅓	(9.5)	7.60	1.66	2.8
Pan	<3.8	(9.5)	0.40	0.41	0.5
Mean Diameter (in.) (mm)			0.737 (19)	0.992 (25)	1.158 (29)
% Passing	¾	(14)	70.7	20.94	10.6
% Passing	1	(25)	91.9	58.44	27.7
% Passing	1½	(38)	100.0	97.04	90.3

Table 3 Properties of stone ballast utilized on single-ply roofs in the United States

This data indicates that commercial stone currently being used as ballast on single-ply loose-laid membranes has a mean diameter of 25mm (0.992 inch) with 58 percent passing a 25mm (1 inch) size and 21 percent passing a 19mm (¾ inch) sieve. Active scour on a 25mm (1 inch) stone commences at about 36 m/s (80 mph) and at about 34 m/s (76 mph) or less for 19mm (¾ inch) stone. As previously indicated these wind speeds will occur within the life of most roofs.

The effects of storms with recorded and documented wind speeds ranging from 27 m/s (61 mph) to 40 m/s (90 mph) is clearly outlined in Figures 3 through 6. This evidence clearly indicates that commercial stone being furnished and installed as ballast on single-ply roof systems is highly susceptible to scour during high rooftop wind speeds which can be expected to occur within the design life of the membrane.

#### STONE BALLAST WEIGHT FOR FULL COVERAGE

Phalen<sup>3,5,15</sup> has demonstrated that the rate of stone application on a single-ply, loose-laid roof membrane can be expressed by the following equations:

$$W = 4.32\gamma_s D_m \text{ (psf)} \quad (6A)$$

$$W = 0.831\gamma_s D_m \text{ (Kg/m}^2\text{)} \quad (6B)$$

where  $\gamma_s$  is the specific gravity of the stone and  $D_m$  is the mean diameter of the stone in inches (6A) or mm (6B). Table 4 indicates the minimum weight of application that is required to accomplish full coverage.

Stone Diameter		Application Rate	
(mm)	(in.)	(Kg/m <sup>2</sup> )	(psf)
19	(¾)	42.3	(8.7)
22	(⅞)	49.3	(10.1)
25	(1)	56.4	(11.5)
38	(1½)	84.5	(17.3)
51	(2)	112.7	(23.1)
64	(2½)	140.9	(28.8)
76	(3)	169.1	(34.6)

Table 4 Application rate for full coverage utilizing stone ballast

The results of stone research at Northeastern University<sup>3</sup> depicted in Table 4, indicate that commercially available stone adjusted for the correct local specific gravity follows Equation 7. In other words, commercially available stone with a mean diameter of 25mm (about 1 inch) can be applied at the rate of 56-60 Kg/m<sup>2</sup> (12 psf) and accomplish full coverage. However, this stone is very susceptible to scour, and can fail at rooftop wind speeds of 36 m/s (80 mph) or less.

#### BASIS OF SUGGESTED STONE BALLAST DESIGN CRITERIA

The data presented in this paper can be summarized as follows:

1. In winds exceeding 26 m/s (60 mph) to 36 m/s (80 mph) small stones (the fraction less than 19mm (¾ inch) become airborne and act as missiles capable of breaking glass and creating other substantive damage. This stone fraction should be specified as 0 percent.
2. Stone that is currently available and used for ballast contains a large fraction of stones smaller than 19mm (¾ inch). Obviously, for normal winds in excess of 26 m/s (60 mph) this fraction must be removed from the stone mixture to eliminate potential flying missiles.
3. Storms from hurricanes and other sources develop wind speeds in excess of 26 to 31 m/s (60-70 mph) at least once in 10 to 15 years. Further, hurricane winds exceeding 40 m/s (90 mph) occur with reasonable frequency. Also hurricane winds come from every direction of the compass. Thus, for design purposes, rooftop level wind speeds range from 26 to 58 m/s (60 to 130 mph).
4. Field evidence indicates that in a given storm the fraction of stone less than 19mm (¾ inch) does move and exposes substantial portions of the membrane, allowing insulation to be displaced and resulting in substantial repair costs.
5. Full stone coverage is a basic design criteria for stone ballast on a loose-laid single-ply membrane.
6. Active stone scour begins when the rooftop wind speed reaches values indicated by Equation 3.

Recognizing these factors, for a safe design, the *minimum criteria* for stone ballast on a single-ply membrane will follow the limiting criteria shown in Table 5.

Rooftop Wind Speed (V <sub>r</sub> )		Minimum Stone Diameter (in.)		Application Rate	
m/s	(mph)	mm	(in.)	Kg/m <sup>2</sup>	(psf)
31	(70)	19	(¾)	42.5	(8.7)
36	(80)	25	(1)	56.2	(11.5)
40	(90)	38	(1½)	84.5	(17.3)
45	(100)	51	(2)	112.9	(23.1)
49	(110)	64	(2½)	140.7	(28.8)
54	(120)	83	(3¼)	183.3	(37.5)
58	(130)	108	(4¼)	239.5	(49.0)

Table 5 Minimum design criteria for stone ballast

The data in Table 5 indicates that when the wind speed at rooftop level (not to be confused with ANSI wind speeds from charts at 10m in height) exceeds 31 m/s (70 mph) serious consideration must be given to the diameter of stone ballast.

At the very least, when stone ballast is used, it should be specified to eliminate all fractions finer than 19mm ( $\frac{3}{4}$  inch) with an appropriate increase in the application rate to accomplish full coverage.

#### REFERENCES

- <sup>1</sup> Phalen, T.E., Jr. "Generic Tensile Properties of EPDM Membranes for Loose-Laid Roof Systems." Roofblok Ltd., Tech. Bulletin No. 8, 1984.
- <sup>2</sup> Doherty, F.W. and Shloss, A.L. "Single-Ply Synthetic Rubber Roofing Membranes." Single-Ply Roofing Technology, ASTM STP 790, 1982.
- <sup>3</sup> Phalen, T.E. and Smith, G.A., Jr. "The Properties of Commercial Stone Ballast Utilized in the United States on Loose-Laid Single-Ply Ballasted Roof Systems." Preliminary Draft Report, Northeastern University, Boston, Mass. September, 1984.
- <sup>4</sup> SPRI. "Single-Ply Roofing Systems: A Guideline for Ballast Specifications." SPRI, Glenview, Ill., 1984.
- <sup>5</sup> Phalen, T.E. "Supporting Documentation for Proposed ICBO Proposal Relative to Wind Speed and Application Rates of Stone Ballast on Single-Ply EPDM Membranes." Northeastern University, Boston, Mass., 1984, presented at ICBO Research Committee Meeting, Tucson, Ariz., July 13, 1984.
- <sup>6</sup> Dove, David. "Market Analysis for Single-Ply Roof Systems." Seminar, Northeastern University, Boston, Mass., May, 1984.
- <sup>7</sup> Davenport, A.G. "Rationale for Determining Design Wind Velocities." Proc. ASCE, J. Struct. Div., E6 ST5, May, 1960.
- <sup>8</sup> ANSI. "Requirements for Minimum Loads in Buildings and Other Structures." Design, 1972, 1982.
- <sup>9</sup> Fujita, T.T. and Stiegler, D.J. "Neoscale Structure of Hurricane Alicia." Alicia One Year Later, Specialty Conference, ASCE, Galveston, Texas, August 16-17, 1984.
- <sup>10</sup> Phalen, T.E. "Wind Design Considerations for Lightweight Concrete Ballast in Loose Laid Roof Systems—A Simplified Approach." Ideal Concrete Block, Waltham, Mass., 1983.
- <sup>11</sup> Mazzagatti, R.D., Landers, P.G., and Walker, R.H. "An Analysis of Hurricane Winds in Florida." Proceedings of Third U.S. National Conference on Wind Engineering Research, Gainesville, Fla., 1978.
- <sup>12</sup> Chien, N., Feng, Y., Wang, H.J. and Slau, T.T. "Wind Tunnel Studies of Pressure Distribution on Elementary Building Forms." Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Ia., 1951.
- <sup>13</sup> Phalen, T.E. "The Influence of Parapet Heights on the Negative Pressure on Roof Systems Created by Wind Related to Single Ply Loose Laid Membranes." Roofblok Limited, Waltham, Mass., 1984.
- <sup>14</sup> Minor, J.E. "Designing for Windborne Missiles in Urban Areas." ASCE Journal of Structural Division, 1979.
- <sup>15</sup> Phalen, T.E. "Analysis of Full Scale Wind Tests for ICBO Research Report No. 4149," Roofblok Limited, Waltham, Mass., March, 1983 and June, 1984.
- <sup>16</sup> Minor, J.E. "Window Glass Research Activity and Their Relation to Hurricane Effects." ASCE Specialty Conference, Alicia One Year Later, Galveston, Texas, Aug. 16, 1984.
- <sup>17</sup> Kind, R.J. "Estimation of Critical Wind Speeds for Scouring of Gravel or Crushed Stone on Rooftops." LTR-LA-142 and LTR-LA-162, National Research Council of Canada, Ottawa, 1974, 1977.
- <sup>18</sup> Kind, R.J., Wardlaw, R.L. "Model Studies of the Wind Resistance of Two Loose-Laid Roof Insulation Systems." LTR-LA-234, National Research Council of Canada, Ottawa, 1979.