Ice Ball Impact Testing of Roofing Materials

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Keywords: Hail, Hail Damage, Roofing, Impact Testing

Abstract

Mechanical launchers have been developed by the authors' firm to propel freezer ice balls (and cubes) at desired velocities toward various roofing products and other objects. Roofing products tested have included the following: asphalt shingles, wood shingles and shakes, concrete and clay tiles, fiber-cement tiles, slate, synthetic tiles, built-up, polymer modified bitumen, plastic single-ply, spray polyurethane foam, and metal roofing. This paper will summarize the history of ice ball launchers and present impact test results on various roofing materials. Our impact test results have compared well to other studies on the subject as well as actual field evaluations of hail damaged roofing.

Introduction

Each year in the United States, hail causes billions of dollars in property damage, including damage to roofs [1]. Thus, there is considerable interest in the insurance and research communities in providing more hail resistant roofing products. As expected, not all roofing products have the same degree of hail impact resistance. This result is due, in part, to the variations in the physical properties of hail as well as the impact resistance of roofing products. Hail variations include the stone size, shape, hardness or density, free-fall velocity, and angle of impact. Roof material variations include product type, age, support condition, impact location, and temperature.

History of Ice Impact Testing

Rigby and Steyn were among the first researchers to publish experimental procedures and test results from launching ice stones at various roofing products [2]. Their study followed the severe hailstorm that struck Pretoria, South Africa in 1949. Three types of ice stones were utilized in their impact tests: spherical, conical at both ends, and a combination of conical and cylindrical. The stones were fired downward using a grenade launcher mounted 6 m above various roofing assemblies. An electrical timing device was utilized to measure the velocity at impact. Twenty-nine types of new roofing assemblies were tested to include metal, wood shingles, natural slate, concrete and clay tiles. Damage was noted when roofing products were perforated, split, or broken. It was concluded that metal roofing had the greatest impact resistance whereas concrete and clay tiles had the least impact resistance.

In 1960, Laurie followed up the work of Rigby and Steyn by using an improved "hail gun" that involved the expulsion of compressed gas regulated by a valve and pressure gauge [3]. Various roofing, glazing, and siding products were impacted using both rounded and cubical ice stones extracted from block ice. Ice stones measured 64 mm in diameter or width, with masses between 100 and 150 g, fired at approximately 46 ms^{-1}. Damage was defined when the roofing products were perforated to allow water penetration. Laurie's conclusions corroborated Rigby and Steyn's, with metal roofing being most impact resistant and tiles being least impact resistant.

Haag Engineering Company began a testing program in 1963 launching ice stones at various grades of new cedar shingles [4]. Eighteen test panels were constructed in 1.2 m squares. Every shingle on fifteen panels was struck with 25 mm spherical or 38 mm cubical ice stones propelled by a shoulder mounted air gun made from steel pipe. Air pressure within the barrel of the gun was regulated and had a quick release valve (Figure 1). The remaining three panels were not impacted and used as a control for the experiment. All 18 test panels were set outdoors to weather naturally for 20 years and examined periodically. Damage was defined as a split in the wood shingles. The study found that splits shingles occurred at the moment of impact and that dents in the wood without initial splitting did not cause future splitting or other deterioration. Dents in the wood were found to recover or erode with time.

Figure 1. First ice ball launcher (IBL-1) constructed by Haag Engineering Co. in 1963 for their impact study on cedar shingles.

In 1969, Greenfeld conducted ice impact tests on various roofing products using a compressed air gun while at the National Bureau of Standards [5]. A timer and actuating levers were mounted on the gun to control the firing time. Polyethylene carriers were constructed to hold various size ice balls within the barrel of the gun. Freezer ice balls were manufactured from molds made by encasing various size fishing floats in resin within a container. Ice balls ranged in size from 25 to 76 mm in diameter and were launched at freefall velocities indicated in Table 1. Roofing products impacted were asphalt shingles, wood shingles, natural slate, asbestos-cement shingles, clay tiles, built-up roofing, and standing seam metal panels. Damage was defined as a fracture of the material. Damage to lightweight asphalt shingles occurred with ice balls between 32 and 38 mm. Heavy weight asphalt shingles had greater impact resistance with the damage threshold increasing to 51 mm ice balls. Smooth-surfaced built-up roofs were damaged with ice balls between 44 and 51 mm with the damage threshold being dependent on the type of substrate. Built-up roofs on softer substrates had lower impact resistance. Gravel-covered built-up roofs survived the largest ice balls in this study. Impact energy was dissipated in the gravel leaving "nests" in the loose gravel surface. Slate, asbestos-cement, and tile roofing had damage thresholds with ice balls between 38 and 51 mm depending on the location impacted.

Table 1. Terminal velocities and energies of hailstones *after Greenfeld* [5].

Diameter (mm)	Terminal Velocity (ms^{-1})	Impact Energy (J)
25	22.3	1.36
32	25.0	5.42
38	27.4	10.85
44	29.6	18.96
51	32.0	29.80
58	34.0	46.01
64	35.7	71.90
70	37.6	109.80
76	39.6	162.70

Haag Engineering's test program was expanded in 1983 to include asphalt shingles, fire-retardant treated wood shingles and shakes, wood fiberboard panels, and aluminum panels [6]. A new ice ball launcher, similar to a spear gun, was designed and fabricated (Figure 2). Elastic tubing was secured to each end of a crossbar that was oriented perpendicular to length of the launcher. The crossbar could be adjusted to different positions along the length of the launcher to allow adjustment of the rubber tubing when the launcher was cocked. Stored energy, and thus the ice ball velocity, was proportional to the amount of tubing stretched. Ice balls rode in a carrier made to fit an aluminum rail that ran the length of the launcher. A locking mechanism at the rear end of the launcher secured the carrier that could be released via a trigger. When the trigger was depressed, the carrier released and accelerated forward, propelled by the contracting rubber tubing. Then as the carrier neared the end of the launcher, it decelerated, allowing the ice ball to travel forward unimpeded. A chronograph fixed to the front end of the gun measured the speed of the airborne ice ball. Ice balls were made using rubber molds and varied from 25 to 32 mm in diameter. Damage to cedar shingles and shakes involved splitting the wood whereas wood fiberboard panels were merely dented with no long-term damage noted. Aluminum panels were dented but the dents were merely cosmetic. From this work, Marshall and Herzog published a protocol on how to properly evaluate hail-caused damage to roofing [7].

Figure 2. Third generation ice ball launcher (IBL-3) constructed by Haag Engineering Co. for their 1983 impact study. A chronograph was mounted to the end of the launcher to measure the velocities of the ice balls.

In 1988, Haag Engineering conducted ice stone impacts on 14 year old built-up roof samples that were protected by an asphalt flood coat and gravel [8]. Impacts were conducted using either 51 mm diameter ice balls or 40 mm wide cubes. A launching device for larger ice stones was needed in order to obtain the necessary impact energies to damage the roofing (Figure 3). So, a pneumatic air gun was constructed from 2.4 m long seamless aluminum tubing with inside diameter of 89 mm. A piston-operated valve assembly was installed within the back end of the aluminum tube. Prior to firing, an ice stone was loaded into the carrier through the front end of the tube. To fire the gun, high pressure air was injected via a valve behind the piston to initiate movement of the piston and carrier. After initial acceleration to the desired speed, the carrier decelerated and stopped, releasing the ice ball to travel unimpeded past a chronograph fixed to the front end of the tube. Target velocities of the ice stones were the same as in Greenfeld's study.

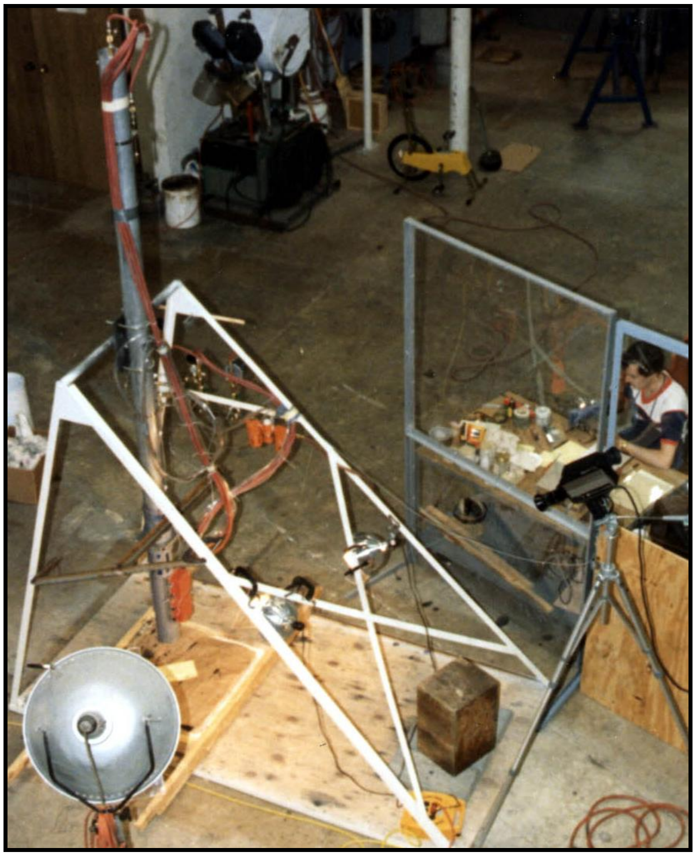

Figure 3. Fifth generation ice ball launcher (IBL-5) constructed by Haag Engineering Co. for built-up roof impacting in 1988.

A total of 94 impacts were made against the built-up roof samples: 76 ballasted with gravel and 18 with both loose and embedded gravel removed prior to testing. For the samples with gravel ballast, the ice ball typically broke apart or shattered upon impact, displacing the loose gravel and forming a divot (crater) in the loose gravel (Figure 4). Larger and faster ice balls created larger and deeper divots in the loose gravel. The largest ice ball impacts removed pieces of the asphalt flood coat, leaving the exposed asphalt surface fragmented and shiny. In no instance was gravel driven downward into the roofing membranes.

Figure 4. Ice ball breaks apart upon impact removing some of the surface gravel and flood coat on a built-up roof. No damage was done to the underlying roofing plies.

Examination of impact zones on roofing samples covered with gravel revealed no impact damage using either 51 mm diameter balls or 40 mm wide cubes. This result was independent of the base material used (poured gypsum concrete, concrete block, or expanded polystyrene insulation). Similarly, no impact damage occurred to roofing samples where all the gravel had been removed (spudded) and placed on top of a poured gypsum deck. However, one of the three impacts by 51 mm diameter ice balls did cause a slight indentation and tear in the top ply of the spudded sample resting on a concrete block base. Similarly, one of three impacts produced by the 40 mm cubical ice stones damaged the spudded sample supported by 51 mm expanded polystyrene insulation. Tears occurred in all plies. Finally, all three impacts of the 51 mm ice balls damaged the spudded samples resting atop expanded polystyrene insulation. This confirmed Greenfeld's observation that softer substrates make the overlying built-up roof more susceptible to impact damage. Also, like Greenfeld's study, our test results indicated that gravel surfacing provided significant impact protection to the built-up membranes.

In 1991, Koontz [9] conducted ice ball impact tests on asphalt shingles, wood shingles, and concrete tiles. A compressed air gun with a quick release valve was utilized. Five sizes of freezer ice balls were manufactured in rubber molds from 19 to 64 mm. Ice ball freefall velocities were utilized from Table 1. Roofing assemblies were struck with angles of impact of 15, 45, and 90 degrees. New as well as old roofing materials were utilized. Impact tests also were conducted on roofing products at different temperatures. Results showed various damage thresholds depending on physical characteristics of the ice balls and roofing products. In 2000, Crenshaw and Koontz followed up this work performing impact tests on several commercial roof products including polyvinylchloride (PVC), thermoplastic olefin (TPO), ethylene propylene diene monomer (EPDM), atactic polypropylene (APP) and styrene butadiene styrene (SBS) modified bituminous membranes [10]. Again, varying impact resistance was found depending on the physical characteristics of the ice balls and roofing products.

Haag Engineering's Current Ice Ball Launcher

The current ice ball launcher utilized at Haag Engineering includes improvements in design such as attachments for multiple elastic tubing and plastic sleds which can propel ice balls from 13 to 57 mm in diameter (Figure 5). An adjustable laser is mounted on top of the launcher to reveal the location of the impact on the target. Plastic and fabric safety shields are mounted on the launcher to provide protection from ricocheting ice balls. Solid ice balls are made in silicone molds (Figure 6).

Figure 5. Seventh generation ice ball launcher (IBL-7) with light emitting diode (LED) sensors (chronograph) developed for impact testing.

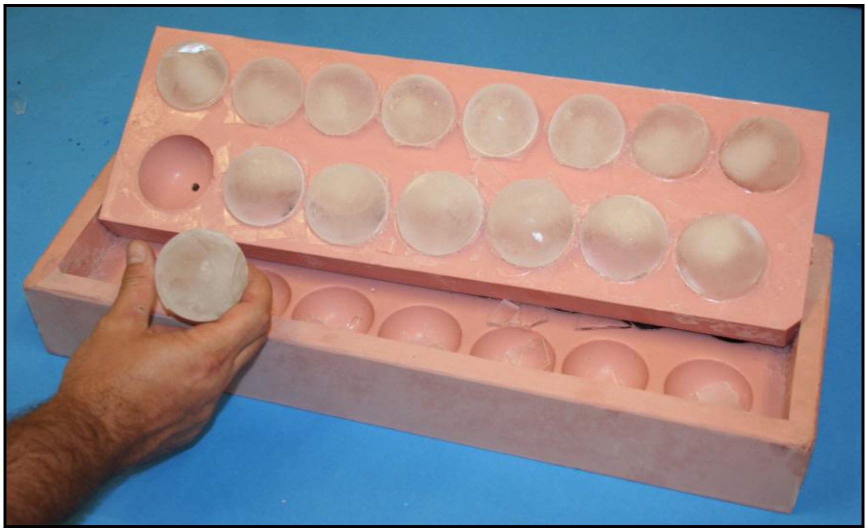

Figure 6. Ice balls are made in silicone molds for impact testing.

Recent Impact Testing

Roofing products tested were: 1) three-tab asphalt shingles with glass fiber mats, 2) three-tab asphalt shingles with organic mats, 3) laminated glass fiber asphalt shingles, 4) cedar shingles, 5) “heavy” cedar shakes, 6) flat concrete tiles, 7) S-shaped concrete tiles, 8) fiber-cement tiles, and 9) built-up gravel covered roofing. The asphalt shingles and cedar shingles were weathered naturally about 11 years; the built-up roofing samples were eight years old. The other roofing products were new. Roofing products were applied to test panels in accordance with manufacturers’ specifications. The panels were covered with plywood decking and/or wooden lath boards or battens and had an asphalt-saturated underlayment if required. The built-up roofing samples also had 13 mm thick perlite insulation board on top of the wooden roof deck. The launcher was utilized to propel solid ice balls that were 25, 32, 38, 44, and 51 mm in diameter. Ice balls of 19 mm in diameter also were utilized for impacting the organic three-tab asphalt shingles. All impacts were made perpendicular to the product at ambient room temperature. A total of ten impacts were made for each size ice ball on each roofing product (usually one impact per unit) until eight of ten (80%) impacts, or more, damaged the roofing product. Impact velocities were within ten percent of nominal freefall velocities as shown in Table 1. Damage was defined as a fracture or breakage of the material.

Results of our ice ball impact tests are shown in Table 2. As expected, the 11-year old asphalt shingles were most susceptible to damage since they were thin and brittle. Aged organic mat-based asphalt shingles were damaged half of the time by 25 mm diameter ice balls, whereas it took 32 mm diameter ice balls to damage the aged glass-fiber mat based asphalt shingles. Thicker, aged laminated shingles were damaged by 38 mm ice balls. The most impact resistant products were the S-shaped concrete tiles and the built-up gravel roofing where ice balls of 51 mm in diameter were needed to initiate damage. In general, the majority of the roofing products we tested (5 of 9) sustained impact damage with ice balls of 32 mm in diameter and all products tested sustained impact damage with 51 mm diameter ice balls. These tests were consistent with those performed by Marshall [11], [12], and summarized by Morrison [13].

Table 2. Ice ball impact test results for various roofing products. Percent of damage is indicated.

Type of Roofing Product	Age (yrs)	25 mm	32 mm	38 mm	44 mm	51 mm
3-tab fiberglass shingles	11	0	60	90	100	100
3-tab organic shingles*	11	50	90	100	100	100
30 yr. Laminated shingles	11	0	0	60	90	100
Cedar shingles	11	0	30	80	100	100
Heavy cedar shakes	0	0	0	50	90	100
Fiber-cement tiles	0	0	20	80	100	100
Flat concrete tiles	0	0	20	50	50	100
S-shaped concrete tiles	0	0	0	0	0	80
Built-up gravel roofing	8	0	0	0	0	30
Number of Products Damaged		1/9	5/9	7/9	7/9	9/9

*no damage at 19 mm.

Roofing Impact Standards

The first roofing impact test standard in the U.S. was developed by Factory Mutual Research Corporation (FMRC) in 1986 and used steel balls instead of ice balls [14]. The FM 4470 standard utilized a 51 mm diameter steel tube supported by a tripod. A 51 mm diameter steel ball weighing 521 g was to be dropped from a height of 1.5 m onto the roofing assembly a minimum of ten times, then the roofing material was examined under ten power magnification for any cracks, splits, separations, or ruptures. The use of steel balls instead of ice balls was a departure from the history of impact testing on roofing products. One reason for the initial hesitation to use ice balls was the lack of uniformity of the ice balls. However, steel balls are harder, heavier, and have more momentum than ice balls of the same size. Thus, as Koontz [9] noted, impacts using steel balls on brittle materials would cause such products to fracture or break at smaller sizes than if impacted with ice balls.

In 1996, Underwriters Laboratories (UL) published an impact resistance standard for roofing products using steel balls [15]. Steel balls of 32, 38, 44, and 51 mm in diameter weighing 127, 218, 358, and 521 g, respectively, are dropped twice onto the roofing assembly from heights of 3.7, 4.6, 5.2 and 6.1 m, respectively. The roofing assembly is to contain the roofing product, underlayment or interlayment, deck, and support members. Impacts on the roofing assembly are to be performed at six locations to include edges, corners, unsupported areas, overlaps, and joints. In order to pass the test, the roofing material shall show no signs of tearing or fracturing to achieve Class 1 (least impact resistant), 2, 3, or 4 (most impact resistant) ratings.

An ice ball impact test standard was approved in 2000, when the FMRC published the standard FM 4473 for roofing products [16]. Ice balls of 32, 38, 44, and 51 mm in diameter weighing 15, 27, 42, and 63 g, respectively, are propelled at velocities of 26, 28, 31, and 34 ms^{-1}, respectively. A minimum of three target locations must be impacted twice to include edges, corners, unsupported areas, overlaps, and joints. Ice balls must be free of air bubbles or cracks. In order to pass the test, the roofing material shall show no signs of breakage that would compromise the roof system to achieve Class 1 (least impact resistant), 2, 3, or 4 (most impact resistant) ratings. Such ice ball impact testing was recognized as the “worst case hailstone”, since hail is generally less dense than freezer ice.

Summary

Laboratory impact testing of roofing products has been performed for more than half a century. Ice stones have been launched with pneumatic guns or sled devices. As expected, not all roofing products have the same impact resistance. Important characteristics of the roofing product are type, age, support condition, impact location, and temperature. Equally important are the parameters of the ice stone to include size, shape, hardness or density, free-fall velocity, and angle of impact. In this paper, we presented a brief history of impact testing of roofing products using freezer ice as well as specific test results. Damage to a roofing product has been defined as a fracture or breakage of the material.

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