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HAIL DAMAGE TO TILE ROOFING

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1. INTRODUCTION

Roofing tile is popular especially in the southern U.S. due to its resistance to fire, heat, and moisture, as well as its long service life. The first clay roofing tiles were produced in Asia and later in Europe several thousand years ago. Hobson (2001) indicated the first clay tiles produced in the U.S. were in 1650 in the upper Hudson River Valley. Concrete roofing tiles didn't appear until around 1848 in Germany and commercial production began soon after in Bavaria. However, within the past twenty years, dozens of new tile products have been developed comprised of lightweight concrete and wood-fiber cement. Many of these newer products have performed poorly when exposed to the weather for only a short period of time. Moisture damage to tiles has involved surface peeling, delamination, erosion, and pitting, just to name a few problems. When a hailstorm occurs, damage inspectors unfamiliar with these products can erroneously conclude that certain anomalies with the roofing tile had been caused by hail.

We have undertaken a study of various roofing tiles in an effort to document the effects of hail. Ice ball impact tests were conducted on many different roofing tiles and compared with our field observations from thousands of roof inspections over the past twenty years. In this paper, we will summarize the characteristics of hail-caused damage to various roofing tiles and distinguish them from conditions that occur in tile manufacturing, installation, and/or weathering.

2. ICE BALL IMPACT TESTING

Laurie (1960) was one of the first to conduct ice ball impact tests on roofing tiles. He produced spherical and cubical ice stones of 2.5 in. (5.1 cm) in diameter and launched them with compressed air using a modified grenade thrower. He impact tested concrete and clay tiles among other types of roofing products.

Greenfeld (1969) conducted a series of ice ball impact tests on various roofing materials using a commercially available compressed air gun. Ice balls in 1/4 in. (.6 cm) increments were made from molds between 1 in. (2.5 cm) and 3 in. (7.6 cm) in diameter. Among the roofing materials tested were asbestos-cement shingles and red clay tiles. He defined failure as a crack in the material and was able to damage 1/8 in. (.3 cm) thick asbestos cement tiles with 1.5 in. (3.8 cm) ice balls and crack unsupported areas on clay tiles with 1.75 in. (4.5 cm) ice balls.

Koontz (1992) performed ice ball impact tests on various concrete tiles using a compressed air gun similar to Greenfeld. He found that all tiles tested exhibited fairly high degrees of impact resistance. Fracture of the material did not occur even with 2.5 in. (6.4 cm) ice balls propelled at around 80 mph (36 ms^{-1}). However, he was able to break the tiles when he increased the velocities of the ice balls to 89 mph (40 m/s^{-1}). He found that flat concrete tiles were more impact resistant than S-shaped tiles.

The authors' firm conducted numerous ice ball impact tests on various concrete tiles beginning in 1992. Additional impact tests were conducted for this study. Our firm developed a mechanical device dubbed the IBL-7 (Ice Ball Launcher – 7th generation) that launched ice balls on a track employing multiple bands of latex tubing (Figure 1). The tubing ensured consistency in launch velocity and the track guided each ice ball to the desired target point. This was an improvement over compressed air guns utilized in earlier tests, as it was difficult to control the launch velocities of the ice balls using compressed air.

An ice ball was placed into a plastic holder that kept the ball in place while it accelerated forward. The holder was stopped at the end of the track allowing the ice ball to continue forward. Desired velocities of the ice ball were obtained by controlling the tension on the latex tubing. The velocities of the ice balls were measured by a chronograph mounted on a tripod at the end of the launcher. Target launch velocities are shown in Table 1. Generally, the ice balls were produced by freezing tap water in molds, and they were harder and denser than natural hailstones (Figure 2).

Figure 1. Ice ball launching (IBL-7) device with light sensors (chronograph) developed for impact testing.

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Ball diameter		Target Velocity		Energy
in.	cm.	Mi./hr.	M/sec.	Ft-lbs.
.75	1.9	42.3	18.9	0.44
1.00	2.5	49.8	22.3	1.43
1.25	3.2	55.9	25.0	3.53
1.50	3.8	61.4	27.4	7.35
1.75	4.5	66.2	29.6	13.56
2.00	5.1	71.6	32.0	23.71
2.25	5.8	76.0	34.0	37.73
2.50	6.4	79.8	36.7	57.48

Table 1. Terminal velocities and energies of ice balls utilized in this study.

Figure 2. Solid ice balls made in rubber molds were utilized for impact testing on roofing products.

3. CONCRETE ROOFING TILE

3.1 Ice ball impact tests

A total of 13 different concrete tile products were tested. Tiles had various profiles including mission S, double S, flat, and flat-ribbed (Figure 3). Each tile had overall dimensions of 17 in. (44 cm) in length, 12-3/8 in. (1.4 cm) in width, and up to 1 in. (2.5 cm) thick. Tiles had interlocking side joints up to 1 in. (2.5 cm) wide by 1/2 in. (1.3 cm) thick and would overlap the adjacent tiles. The tiles were installed on test panels per manufacturer specifications and subjected to ice ball impacts using the IBL-7. Tiles were impacted perpendicularly in the field, along the overlaps, and in the lower right corners (when looking upslope) using ice balls ranging from .75 to 2.5 in. (1.9 to 6.4 cm) in diameter.

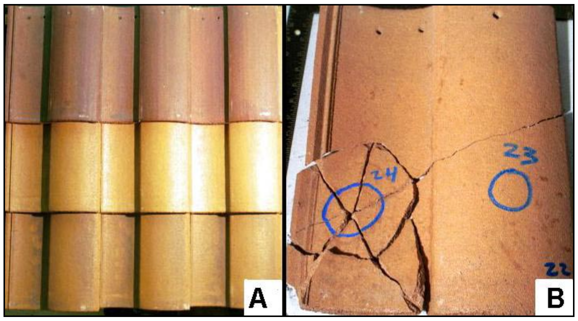

Figure 3. Concrete tile testing: a) sample test panel, and b) tile breakage after ice ball impact.

Damage to the concrete tile was defined as a fracture in the material. Typically, multiple irregular fractures emanated from the impact point. Fractures that occurred above the headlap were functional damage as the water shedding ability of the tile had been compromised. Table 2 shows a summary of our ice ball impact tests for one of the concrete tile products.

CONCRETE S-TILE
ICE BALL IMPACT TEST RESULTS

No.	Dia. (in.)	Weight (lbs.)	Speed ft/sec.	Energy (ft-lbs.)	Damage (Yes/No)
1	1.50	.0575	94	7.90	No
2	1.50	.0605	92	7.96	No
3	1.50	.0600	92	7.89	No
4	1.75	.0990	100	15.39	No
5	1.75	.0930	101	14.74	No
6	1.75	.1020	99	15.54	Yes
7	2.00	.1505	111	28.82	Yes
8	2.00	.1400	112	27.29	No
9	2.00	.1385	113	27.49	Yes

Table 2. Concrete S-tile ice ball impact test results on one of the 13 different products tested.

In summary, none of the concrete tiles tested were fractured by 1 in. (2.5 cm) diameter ice balls, even in their most sensitive locations. Four of the 13 tiles were fractured at their corners with ice balls as small as 1.25 in. (3.2 cm) in diameter. Six of the 13 tiles remained unbroken when impacted with 1.50 in. (3.8 cm) diameter ice balls. Ice balls of 2.5 in. (6.4 cm) in diameter broke all tiles. These test results correlated well with our observations of concrete tile roofs after actual hailstorms (Figure 4).

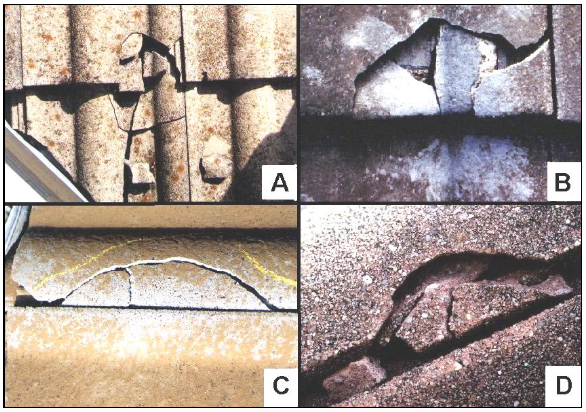

Figure 4. Hail damage to concrete tiles: a) shattered tiles from a single impact, b) shattered tile edge associated with a hail-caused spatter mark, c) large half-moon shaped fracture along the tile overlap, and d) small half-moon shaped fracture along the tile overlap.

3.2 Curved corner fractures in concrete tiles

The authors have discovered that curved corner fractures are inherent in many concrete tile roofs. These cracks emanate from the lower right corners of the tiles and have a variety of causes (Figure 5). We have found right corner fractures with all types of interlocking tile profiles. Occasionally, inspectors mistakenly identify this phenomenon as hail damage. Close examination usually reveals algae or dirt in the fractures thereby indicating old damage. Sometimes, tile corners are reattached with caulking or cement.

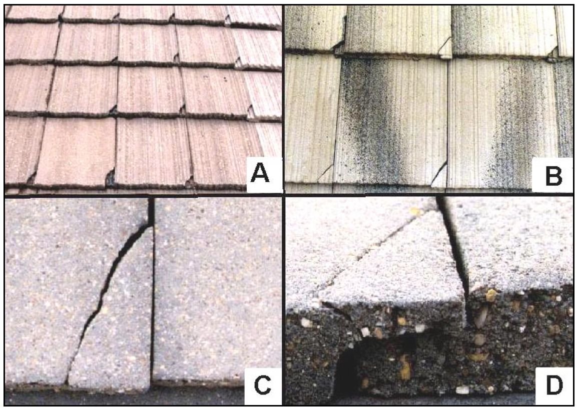

Figure 5. Curved right corner fractures in concrete tiles that were not the result of hailstone impact.

One cause of right corner fractures is shunting the tiles together so that they butt tight with no room for expansion. Tiles need room to expand with increasing temperature and moisture. One can expect a 50 ft. (15 m) length of tiles to expand roughly .2 in (.5 cm) due to a change of 50 F (10 C). Without providing room to accommodate expansion, tiles press against each other. The resulting strains can fracture the thinner overlap region on the tile, especially at the lower right (when looking upslope) corners. Thus, tiles with interlocking side joints should be installed with maximum "play" in order to accommodate for lateral movement. We also have found that persons walking on the tiles can also cause right corner fractures. In most instances, the fractured corners remain below the headlap regions and do not result in water infiltration. However, less common secondary fractures have been discovered in the tile overlaps extending above the headlap regions (Figure 6).

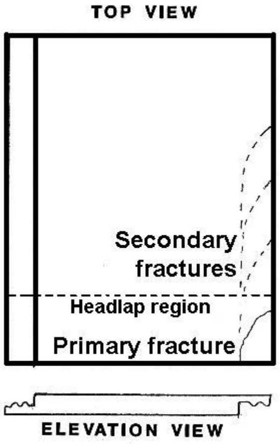

Figure 6. Primary and secondary right corner fractures in flat concrete tile.

There are two additional factors in the design of concrete tiles that can promote right corner fractures. One factor is a shrinkage crack that forms as the tile dries unevenly. Tiles with interlocking side joints do not have a uniform thickness in cross section. Thus, as these tiles dry, the thin, outer edges of the tiles dry first and the thicker portions dry last. In particular, the interlocking side joints cure first since this area has the greatest surface area-to-volume ratio. In contrast, the thicker portion of the tile, containing head and nose lugs, dries last since this area has the smallest surface area-to-volume ratio. The relative time differences in drying/curing can create internal stresses that lead to shrinkage cracks (Figure 7). The authors have found small shrinkage cracks in new tiles. The cracks became more obvious when tiles were misted with water and the water-filled cracks dried slowly.

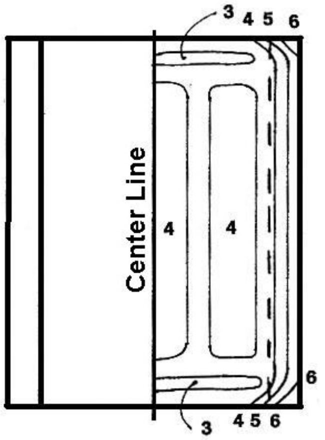

Figure 7. Surface area-to-volume ratios shown in right half of a flat tile. In general, the higher the area-to-volume ratio, the quicker the tile dries. In this case, the overlap dries first, especially at the corners.

Another factor that can cause right corner cracks is a small nub that extends from the lower left corner on the adjacent tile (Figure 8). This nub is formed during the manufacturing process when the tile is trimmed. The nub acts as a stress concentration point as it bears against the adjacent tile. The nub eliminates the room necessary to accommodate for expansion due to increasing temperature and moisture. The resulting strains promote curved cracks across the overlapping portion of the tile.

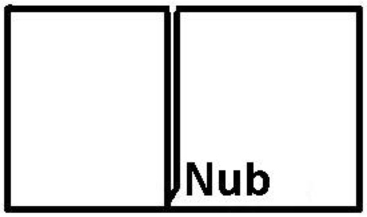

Figure 8. Nub projecting from bottom left corner of adjacent concrete tile can produce a stress concentration point on the right corner of the adjacent tile. This nub also can be observed in Figure 5 (d).

3.3 Additional concrete tile defects

There are a number of additional tile deficiencies caused during the manufacturing process or installation (Figure 9). Some concrete voids have rounded forms that can be mistaken for hail damage. Persons walking improperly on the tiles can break the tiles across their widths. When walking on a tile roof, it is best to step along the lower portion of the tile, where underlying lugs provide firm support. In contrast, the center of the tile has little underlying support and is easier to break under foot.

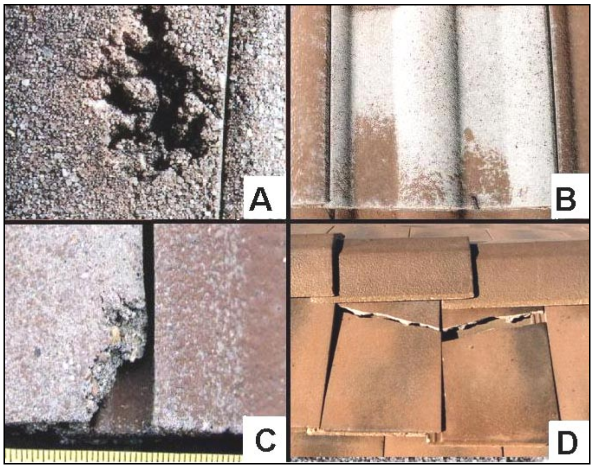

Figure 9. Concrete tile defects not caused by hail: a) concrete void, b) lack of slurry coat, c) missing tile corner, and d) broken tiles from foot traffic.

4. CLAY ROOFING TILE

4.1 Ice ball impact tests

A test panel with Spanish clay tiles was constructed and impacted with various size ice balls using the IBL-7. The tiles were hung on nails on a wooden roof deck (Figure 10). Tiles were impacted perpendicularly in the field and in the lower right corners using ice balls of 1.25 and 1.5 in. (3.2 and 3.8 cm) in diameter. Damage to the tiles involved breaking or shattering of the product. Multiple fractures occurred in the tiles and fractures were irregular, emanating from the impact point.

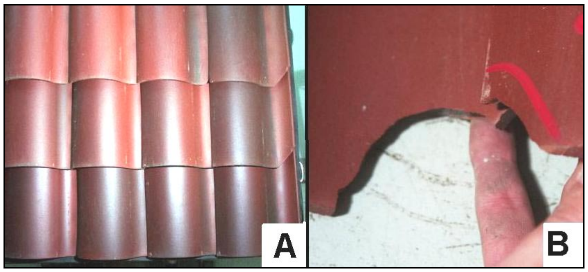

Figure 10. Clay tile testing: a) test panel, and b) shattered nose or bottom edge of tile after impact.

Table 3 summarizes our impact test results on clay roofing tiles. No tile fractures occurred when impacted with 1.25 in. (3.2 cm) ice balls. However, all tile corners broke with 1.50 in. (3.8 cm) ice balls. Field areas of the tiles were more impact resistant than the tile edges.

CLAY S-TILE
ICE BALL IMPACT TEST RESULTS

No.	Dia. (in.)	Weight (lbs.)	Speed ft/sec.	Energy (ft-lbs.)	Damage (Yes/No)
1	1.25	.0335	85	3.76	No
2	1.25	.0345	85	3.78	No
3	1.25	.0350	84	3.84	No
4	1.50	.0595	95	8.35	No
5	1.50	.0610	93	8.20	No
6	1.50	.0610	94	8.38	No
7	1.50	.0600	92	7.96	Yes*
8	1.50	.0605	93	8.07	Yes*
9	1.50	.0615	93	8.27	Yes*

*Corner impacts

Table 3. Clay S-tile impact test results.

4.2 Clay tile deficiencies

Clay tiles are prone to pitting or spalling due to freeze-thaw effects especially if they are deteriorated. Small voids and material inclusions absorb moisture and expand during freezing conditions. Some of these spots can take on rounded forms and be misidentified as hail-caused damage. Occasionally, rough areas on tile surfaces form when they are manufactured (Figure 11).

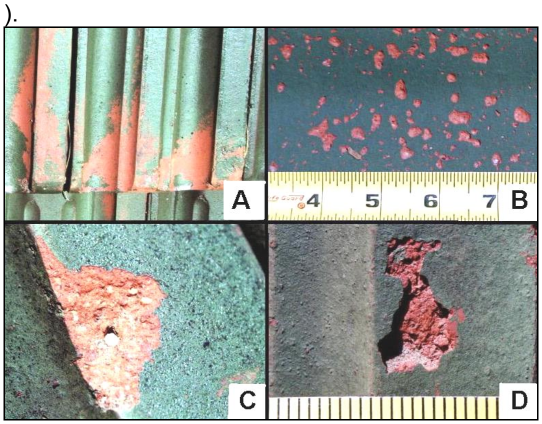

Figure 11. Clay tile deficiencies not caused by hail: a) lack of glazing, b) pitting, c) spalling, and d) void in the tile when made.

5. WOOD FIBER-CEMENT ROOFING TILE

5.1 Ice ball impact tests

A test panel with wood fiber-cement tiles was constructed and impacted with various size ice balls using the IBL-7 (Figure 12). Individual tiles were 18 in. long (46 cm) and 8 or 12 in. wide (20 or 30 cm) by 1/4 in. (.6 cm) thick. Tiles had a wood grain pattern on their top surfaces that resembled cedar shingles. The tiles were fastened to a wooden roof deck over a felt underlayment. Tiles were impacted perpendicularly in the field and in the lower corners using ice balls of .75, 1, and 1.25 in. (1.9, 2.5, and 3.2 cm) in diameter. Damage to wood fiber-cement tile involved an indentation with fracturing of the tile layers.

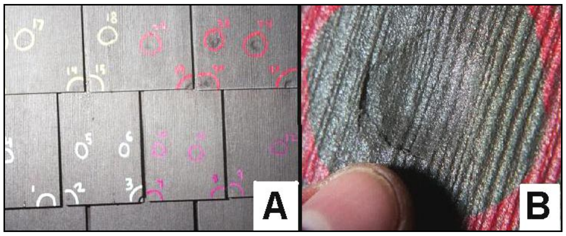

Figure 12. Wood fiber-cement testing: a) test panel, and b) indentation produced by 1.5 in. (4.5 cm) ice ball.

Table 4 summarizes our impact test results on wood fiber-cement roofing tiles. No tile fractures occurred when impacted with .75 in. (1.9 cm) ice balls. However, all tiles were indented or fractured with 1.50 in (3.8 cm) ice balls.

WOOD FIBER-CEMENT TILE
ICE BALL IMPACT TEST RESULTS

No.	Dia. (in.)	Weight (lbs.)	Speed ft/sec.	Energy (ft-lbs.)	Damage (Yes/No)
1	1.00	.0175	76	1.57	No
2	1.00	.0180	76	1.62	No
3	1.00	.0185	76	1.66	No
4	1.25	.0335	84	3.67	No
5	1.25	.0340	84	3.73	No
6	1.25	.0340	86	3.91	No
7	1.50	.0605	93	8.13	Yes
8	1.50	.0615	93	8.27	Yes
9	1.50	.0620	95	8.70	Yes

Table 4. Ice ball impact test results on wood-fiber cement tile.

We found that wood fiber-cement tiles were softer than their concrete and clay counterparts and readily dented. There also were brittle-type fractures with half moon-shaped fractures along the tile edges. These observations correlated well with our field inspections of such roofs (Figure 13).

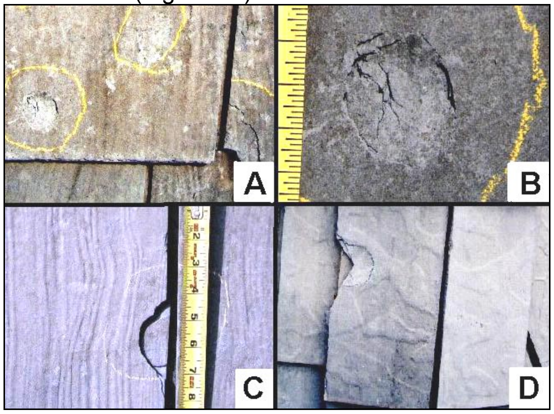

Figure 13. Hail damage to wood fiber-cement tiles: a) indentations, b) closer view of indentation, c) half moon-shaped fracture at edge, and d) broken ridge tile.

5.2 Deterioration of wood fiber-cement tile

The authors have determined that a number of wood-fiber cement tile products have deteriorated rapidly with exposure to moisture and freeze/thaw effects. These thin tile products can peel, erode, and delaminate in as little as six years of normal weather exposure. Some aspects of tile deterioration take on rounded forms that can be misidentified as hail-caused damage (Figure 14). Murphy (2002) discusses the deterioration effects of blue-green algae on fiber-cement tiles.

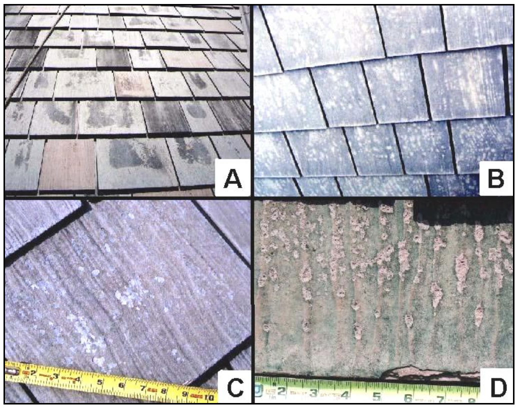

Figure 14. Deterioration effects on wood fiber-cement tiles, not caused by hail: a) dark blotches, b) white blotches, c) surface peeling, and d) pitting/erosion as well as edge delamination.

5.3 Mechanical damage to wood fiber-cement tiles

Wood fiber-cement tiles frequently are installed on steep roof slopes that are not walkable. Installers attach toe-boards to the roof in order to install the roofing tiles and removed them after the tiles are installed. Since the tiles are relatively soft or brittle, they are relatively easy to damage. We have identified various mechanical damages to wood fiber-cement tile roofs caused when the roof was installed. Such problems include broken corners, gouges, nail holes, overdriven staples, and footfall damage (Figure 15).

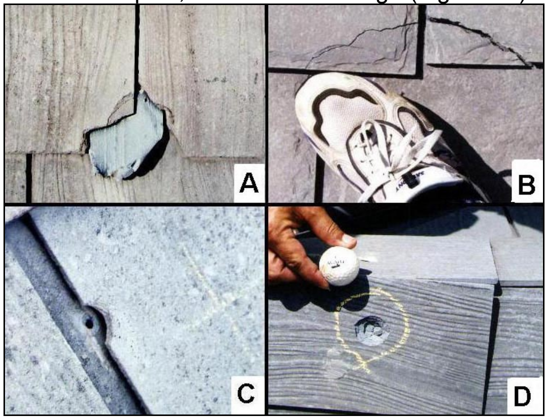

Figure 15. Mechanical damage to wood fiber-cement tiles: a) broken corners and metal toe-board bracket, b) foot broken tiles, c) chipped tile edge and nail hole, and d) golf ball impacts.

We also have found a number of cases where the tiles were indented by errant golf balls from a nearby golf course. Such damage was not randomly distributed on the roof but concentrated on the roof slope nearest the golf course (Figure 16). The indentations all were similar in size and shape, and a golf ball could fit well inside the indentations. Hail falls in various sizes and shapes and would not cause such damage.

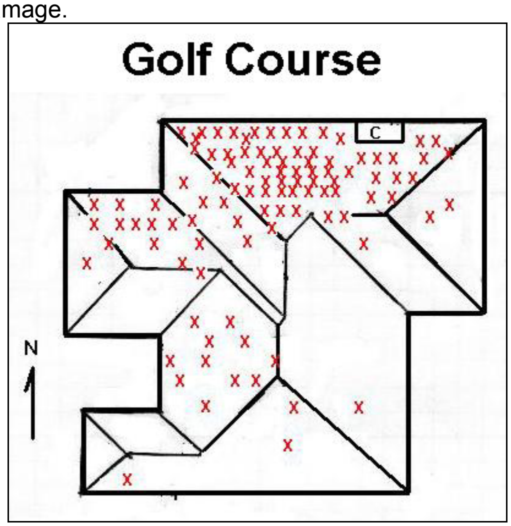

Figure 16. Case where errant golf balls damaged the roof tiles as noted by Xs.

6. ASBESTOS-CEMENT ROOFING TILE

6.1 Ice ball impact testing

Asbestos-cement roofing tile no longer is manufactured in the U.S. due to health concerns. However, there are still a number of older buildings covered with this product. These tiles have been known to last more than 50 years. Asbestos resistance to decay has made it desirable as a roofing product. We have encountered a number of questions about the characteristics of hail-caused damage and whether hail impact of the roofing tile can lead to the exposure or spreading of asbestos fibers.

In an effort to determine the impact resistance and characteristics of hail damage of this product, a test panel was constructed. Flat asbestos-cement tiles were 13.75 in. (34.9 cm) long by 9.25 in. (24.5 cm) wide by 1/8 in. (.32 cm) thick. The tiles were hung from nails driven into a wooden roof deck over felt underlayment. Tiles were impacted perpendicularly in the field, along the bottom edges, and in the lower corners using ice balls of 1.25, 1.5, 1.75 and 2 in. (3.2, 3.8, 4.4, and 5.1 cm) in diameter. Damage involved fracturing the tile.

Table 5 summarizes our impact test results on asbestos-cement tiles. We found these tiles were quite resistant to hailstone impact. No tile fractures occurred when impacted with 1.5 in. (3.80 cm) ice balls. However, tile corners began breaking when impacted by 1.75 in. (4.5 cm) ice balls.

ASBESTOS-CEMENT TILE
ICE BALL IMPACT TEST RESULTS

No.	Dia. (in.)	Weight (lbs.)	Speed ft/sec.	Energy (ft-lbs.)	Damage (Yes/No)
1	1.25	0.034	85	3.76	No
2	1.50	0.058	93	7.80	No
3	1.50	0.058	93	7.80	No
4	1.50	0.058	93	7.80	No
5	1.50	0.058	92	7.76	No
6	1.75	0.101	101	16.01	Yes
7	1.75	0.099	101	15.62	No
8	1.75	0.099	102	15.83	Yes
9	2.00	0.147	113	29.17	Yes

Table 5. Ice ball impact test results on asbestos-cement tile.

Asbestos-cement roofing tiles had the greatest hail resistance among cementitious products tested in spite of its small thickness. This conclusion has also been confirmed in our field inspections of asbestos-cement tile roofs (Figure 17).

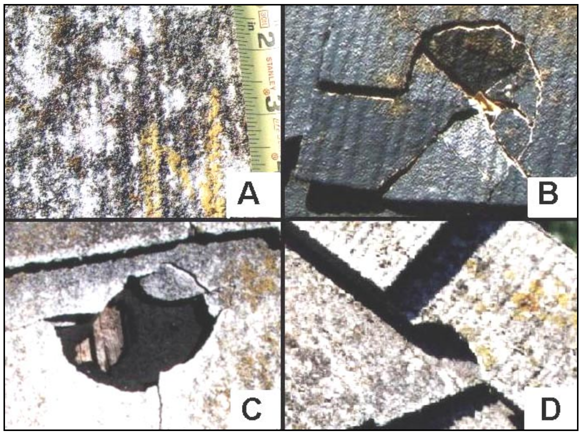

Figure 17. Hail impacts to asbestos-cement products: a) hail-caused spatter marks resulted in no damage, b) indentation with fractures, c) puncture, and d) chipped edge on ridge tile.

Spurny (1989) indicated that asbestos-cement roofing tiles contain up to 12 percent of chrysotile asbestos. He points out that such fibers constantly shed from the tile surfaces due to the eroding action of the wind, rain, sunshine, frost, and even exposure to airborne pollutants. Bornemann and Hildebrandt (1986) studied the wearing rates of uncoated asbestos-cement roofing tiles and found an average release rate of asbestos-cement fibers was 3 g/m^2 per year. They cited rainwater as the primary cause of releasing asbestos-cement fibers.

While it may be possible that hail impacting eroded asbestos-cement roofing can release fibers into the air, this doesn't seem to be any more than by normal weathering. We are not aware of any scientific studies to date that would indicate that hail merely striking a roof (and leaving spatter marks) causes damage to the tile. Therefore, we currently do not consider asbestos-cement tile as hail damaged unless it is fractured.

6.2 Other anomalies of asbestos-cement tiles

As mentioned previously, asbestos-cement tiles are quite resistant to the effects of weathering. However, the surface of the product provides a base for growing algae, fungus, and lichens. Also, as the tile wears, it may exhibit erosion of its surface layer as well as edge delamination. These effects can be erroneously attributed to hail damage. The tile also is susceptible to foot traffic damage, especially at tile corners or in areas where the tile is elevated and has less underlying support. Recent fractures can be distinguished from older fractures by the extent of discoloration on the exposed fracture surfaces. Tiles broken recently exhibit fresh, unweathered surfaces whereas tiles broken quite some time ago usually are discolored with algae, fungus, lichens, or dirt (Figure 18).

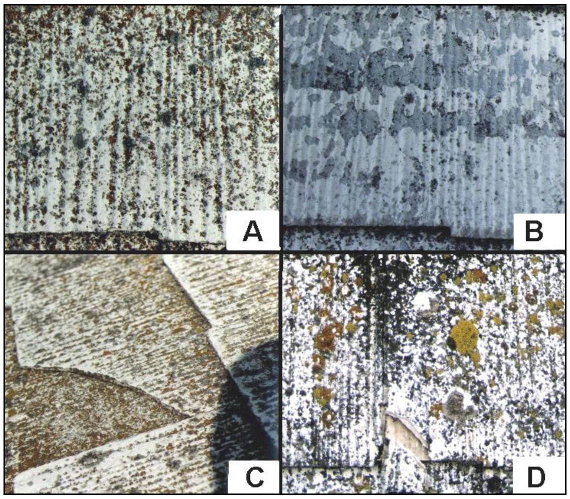

Figure 18. Non-hail caused anomalies on asbestos-cement tiles: a) algae, b) erosion of coated tile, c) old broken tile, and d) new broken tile corner from foot traffic.

7. SUMMARY

A study has been conducted on the effects of hail on various roofing tiles. In this paper, we presented test results regarding ice ball impacts against clay, concrete, wood-fiber cement, and asbestos-cement roofing tiles. Ice balls of various sizes were propelled at different tile targets by a specially designed mechanical launcher. The velocities of the ice balls were carefully monitored and recorded. Each of the roofing products tested exhibited certain levels of impact resistance. For example, ice balls of 1 in. (2.5 cm) in diameter or less resulted in no damage to any of the tested roofing products. We found the damage threshold for most of the roofing products tested was about 1.5 in. (3.8 cm) in diameter.

The characteristics of hail impact typically involved breakage of the tile resulting in multiple irregular fractures emanating from the impact point. However, softer wood-fiber cement tiles were indented. Generally, tile corners were more susceptible to breakage than field portions of the tile by smaller ice balls. Fractured tiles were considered as damaged.

We also presented examples of non-hail type damage and anomalies to various roofing tiles attributed to weathering, installation, and manufacturing. This was done in an effort to aid damage inspectors in distinguishing hail-caused damage from other types of conditions.

8. ACKNOWLEDGEMENTS

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