

INTEGRATING RECYCLED GLASS CULLET IN ASPHALT ROOF SHINGLES TO MITIGATE HEAT ISLAND EFFECT

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ABSTRACT

As an approach to mitigate the harmful effects of Urban Heat Island (UHI), the use of glass cullet in the production of asphalt roof shingles has the potential to be employed as a cool roof strategy. The objective of this study was to test the hypothesis that the use of recycled glass increases solar reflectance index (SRI) without affecting the performance of asphalt roof shingles. In order to evaluate the feasibility of recycled glass for alternative uses, the engineering properties of glass cullet were investigated and compared to conventional aggregates used in the production of asphalt roof shingles. Laboratory samples were then prepared in order to measure solar reflectance properties and strength performance of conventional and recycled glass roof shingles. It is shown that while the use of recycled glass as a replacement to standard ceramic coated black roofing granules on the top surface of asphalt shingles results in an increased SRI, the addition of white pigment powder (anatase ultra fine particles passing mesh #320) mixed together and applied with the surface granules improves reflectance values to meet the cool roof threshold.

CHAPTER 1 – INTRODUCTION

Elevated temperatures during the summertime leads to thermal discomfort, human health issues, and increased consumption of energy demand for cooling purposes. In urban areas, the phenomenon of heat island, which is the thermal gradient difference between developed and surrounding undeveloped areas, is becoming increasingly more intense. Projections demonstrate that many urban areas around the world will experience daytime temperature increases of up to 6°C as a result of heat islands (Kültür and Türkeri 2012).

Development of the earth's surface and the use of high solar radiation absorbing materials are causes of heat island effect, especially in areas where there is a high density of buildings and urban structures. Impacts to the local microclimate both on the surface and in the atmosphere are caused by changes in the thermal properties of building materials and pavements and the removal of natural vegetation (Bretz, Akbari and Rosenfeld 1997).

Shade from trees and green roof strategies are practices that mitigate heat island effect, provide thermal comfort, reduce energy demand, and add aesthetic value to the environment (Saadatian, et al. 2013), but they are not sufficient as a sole solution to the problem. Exposed and highly absorptive materials used on roofs are a major contributing factor that increases heat island effect and cooling demands in urban areas. Roofing materials collect energy from the sun, which results in increased temperatures on and adjacent to the surface. Experiments indicate that highly absorptive roofs (i.e. roofs that absorb 95% of the incident solar flux) can have a surface temperature as much as 60°C higher than the surrounding ambient air (Konopacki and Akbari 2001). This high amount of solar absorptance may also cause heat gains into buildings through a low-grade building envelope, and heat gain through a roof can be a dominant component of the total building cooling load (Akbari, Konopacki and Pomerantz 1999). This increased heat load is

maximized when the materials that comprise the building envelope include dark colored surfaces and have poor or no insulation.

One solution to this problem in the roofing industry has been the use of solar reflective materials. Solar reflective materials (i.e. cool roofs) maintain low surface temperatures by increasing the exterior albedo, which reduces heat transfer through the building envelope. For roofing materials to be regarded as cool, the solar reflectance must exceed a specified threshold, which for asphalt shingles on sloped roofs is often taken to be 0.25 (Berdahl, Akbari, et al. 2012).

The widespread use of cool roofs can save energy, mitigate urban heat islands, and slow global warming by cooling the roughly 20% of the urban surface that is roofed (Levinson, Akbari and Berdahl 2010). Data has shown that summer energy savings of cool roofs can result in savings of up to 70% for an individual building due to lower cooling demands (Bretz, Akbari and Rosenfeld 1997). Roofs with high solar reflectance and high infrared emittance will reduce cooling energy consumption and mitigate the heat island effect, especially in hot and sunny urban environments (Kültür and Türkeri 2012).

With rising energy prices, the potential exists to employ cool roof strategies that are beneficial to the environment, the user, and industry. Therefore, there is an opportunity in the construction and roofing industry to develop a highly-reflective asphalt roof shingle using recycled materials that enhances performance characteristics and is economically and environmentally beneficial.

1.1 Problem Statement

The reuse of glass cullet, which is crushed and furnace-ready scrap glass, is economically and environmentally beneficial. Glass is 100% recyclable, can be recycled endlessly without loss in

quality, and of the 11.5 million tons of glass in the municipal solid waste stream in 2011, approximately 28% was recovered for recycling (U.S. Environmental Protection Agency 2013).

The use of glass cullet is a promising technology that aims to increase the reflectivity of materials used in asphalt roof shingles. However, the application of this technology in asphalt roof shingles is still in its infancy, and many environmental, design, and operational factors still require further evaluation. Furthermore, many factors have not been investigated such as understanding the various interactions that occur when blending traditional roofing materials with recycled glass cullet.

1.2 Objectives

To address the aforementioned problem statement, the objective of this study was to test the hypothesis that the use of recycled glass cullet in asphalt roof shingles enhances solar reflectance without affecting performance. This project proposes a design that incorporates discarded glass into asphalt roofing shingle products, which will help reduce building related waste and construction and demolition debris (C&D). Ultimately, this project aims to develop a new technology that enhances shingle manufacturing and performance by: (a) evaluating the suitability of using recycled glass cullet in roof shingles; (b) measuring the reduction in thermal loads and heat island effects based on the proposed recycling approach; and (c) determining the optimum blending ratios for the proposed glass-cullet modified shingles.

1.3 Research Approach

To achieve the objectives of this study, glass cullet from contrasting sources were obtained and characterized, and then shingle samples were prepared using varying proportions of air-blown asphalt, glass cullet, fiberglass matting, and ceramic-coated granules to measure solar reflectance

and performance requirements. The proposed research methodology consisted of ten tasks split over two project phases.

Phase 1: Characterize the mechanical and reflectance properties of glass cullet. The objective of this task was to characterize the mechanical and reflectance properties of recycled glass cullet collected from C&D processing plants across the country. After the sources of glass cullet were collected, mechanical and reflectance characteristics were analyzed, and then the glass was ground for use in asphalt shingles.

Task 1: Collection of recycled glass cullet. Sources of glass cullet were collected from C&D processing plants. Three contrasting sources of recycled glass cullet were collected and consisted of two different sources of clear glass cullet and one source of green glass.

Task 2: Grind the collected recycled glass cullet. In order to match the gradation of conventional shingles, the glass cullet fragments sizes were reduced with the use of a commercial quality blender. The three recycled glass cullet sources were then ground to smaller sizes, sieved, and then separated to match the particle sizes of the conventional aggregates used as top surface granules, backdust, or filler material. The following U.S. Standard Mesh sieves were utilized: #4, #8, #10, #16, #20, #30, #40, #50, #80, #100, and #200.

Top surface granules resemble coarse sand and consist of particles passing through U.S. Standard Sieve Mesh #8 (2.36mm) and retained on #30 (595 μ m). Backdust particles pass through U.S. Standard Sieve Mesh #30 (595 μ m) and are retained on #200 (75 μ m). Filler material consists of particles passing through U.S. Standard Sieve Mesh #100 (150 μ m) and retained on #325 (45 μ m).

Task 3: Determine grain size distribution. To determine the particle size distribution, grading, and fineness modulus of glass cullet and conventional aggregate, sieve analyses were

completed using the Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM C136). Figure 1 shows the sieves and mechanical sieve shaker utilized.



Figure 1 Mechanical Shaker and Sieves

The three sources of recycled glass cullet (one green and two clear glass) collected from C&D plants were analyzed prior to being reduced to smaller fragments using the following U.S. Standard Mesh sieves: 1", 3/4", 1/2", 3/8", #4, #8, #16, #20, #30, #50, #100, and #200. The percentage of material retained and passing each sieve was recorded, and each analysis was repeated three times in order to determine average particle size distribution.

In order to classify glass cullet using the Standard Practice for Classification of Soils for Engineering Purposes (ASTM D2487), the coefficient of curvature (C_c) and the coefficient of uniformity (C_u) were calculated. The following formulas were used, where D_{60} , D_{30} , and D_{10} correspond to the particle diameters that are 60%, 30%, and 10% finer on the cumulative particle-size distribution curve.

$$\text{Coefficient of Curvature } (C_c) = \frac{(D_{30})^2}{(D_{10} \times D_{60})}$$

$$\text{Coefficient of Uniformity } (C_u) = D_{60}/D_{10}$$

The fineness modulus of recycled glass cullet was determined in accordance with the definition provided in the Standard Specification for Concrete Aggregates (ASTM C33). In order to calculate the fineness modulus, the sum of the cumulative percentages retained on the following U.S. Standard Mesh sieves was divided by 100: 3/4", 3/8", #4, #8, #16, #30, #50, and #100.

$$\text{Fineness Modulus} = \frac{\text{Sum of Cumulative \% Retained on Designated Sieves}}{100}$$

For the material finer than the 75µm, hydrometer analyses were conducted by means of the Standard Test Method for Particle-Size Analysis of Soils (ASTM D422). The glass particle size distribution curves and fineness modulus were then compared to conventional aggregates, which included ceramic coated top surface granules, crushed limestone backdust, and high calcium limestone filler material.

Task 4: Test the engineering properties of glass cullet. Each glass cullet source was characterized by identifying the density, specific gravity, absorption, void content, and soundness. The density, specific gravity, and absorption of the fine material was determined by the use of the Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption (ASTM C128).

To compare the average specific gravity and absorption of glass cullet particles to conventional aggregate, the gravimetric (pycnometer) procedure was completed, as referenced in the Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate (ASTM C128). Figure 2 shows the mold and tamper for surface moisture test. This test was completed for the following fine aggregate used to produce laboratory shingle samples: green glass, clear glass 1, clear glass 2, ceramic coated granules, crushed limestone, and limestone filler material. Tests were completed three times for each aggregate type.



Figure 2 Surface Moisture Test to Determine Specific Gravity and Absorption

To calculate specific gravity on the basis of oven dry (OD), saturated surface dry (SSD), and apparent conditions, four testing measurements were required: Mass of oven dry specimen (g), mass of pycnometer filled with water (g), mass of pycnometer filled with specimen and water (g), and the mass of the surface dry specimen (g). Specific gravity (OD) is the ratio of the density of the oven dry specimen to the density of water, specific gravity (SSD) is the ratio of the density of the saturated surface dry specimen to the density of water, and apparent specific gravity is the ratio of the density of the impermeable portion of the specimen to the density of water.

The same procedure was completed for measurements of absorption, which is based on the difference between the masses of the saturated surface dry specimen and the oven dry specimen. The absorption measurement is a reading of the increase in mass due to penetrating water into the pores with no water on the surface of the particles.

The uncompacted void content of a fine aggregates were determined using the Standard Test Methods for Uncompacted Void Content of Fine Aggregate (ASTM C1252). Figure 3

shows the cylindrical measure, funnel apparatus, and the metal spatula used during the experiment. The fine aggregates were sieved and separated by particle size as used on shingles as top surface granules, backdust, and filler material. Test Method C, which accounts for as received grading was then completed to determine the average uncompacted voids for each source of glass as compared the corresponding conventional aggregates. Tests were completed three times for each source.



Figure 3 Void Content Apparatus

To estimate the soundness of recycled glass and conventional aggregate, samples were exposed to sodium sulfate to simulate freeze-thaw weathering conditions, as referenced in the Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate (ASTM C88). A quantitative evaluation of fine aggregates was conducted by separating and recording the weight of each type of aggregate retained on the following U.S. Standard Mesh sieves numbers: #4, #8, #16, #30, and #50.

The aggregates were then submerged for 18 hours and then oven dried to a constant weight. The process was completed for 5 cycles and percent losses per sieve measurements were

recorded. Tests were completed three times for each aggregate type. The test was completed for green glass, clear glass 1, and clear glass 2 on all sieves listed above. For comparison to conventional aggregates, ceramic coated surface granules were used for the #8, #16, and #30. Crushed limestone backdust was utilized on the #50, and no conventional aggregate testing was completed for the #4 sieve. Figure 4 shows samples prepared for immersion in the sodium sulfate solution.



Figure 4 Soundness Testing of Aggregates

Task 5: Compare the surface reflectance of glass cullet and conventional top surface granules. Reflectance can be estimated using a known measurement of a light source using a lux meter. The following equation was used to calculate initial reflectance measurements.

$$\rho = \frac{L\pi}{E}$$

Reflectance of the specimen is represented by ρ , luminance of the port in candelas per square meter is L , and the illuminance of the known source of light is E (Hiscocks 2011).

Phase 2: Prepare roof shingles in the laboratory and conduct reflectance and durability testing. For proper performance, shingles must be resistant to tearing, warping, and shrinkage when installed (IKO 2012).

Task 6: Determine the blending proportions of recycled glass cullet and conventional minerals. Various proportions of glass cullet were utilized in lieu of and with conventional

mineral aggregate and used as top surface granules, backdust particles, and mineral filler material.

Task 7: Prepare shingle samples. A typical asphalt roofing shingle consists of a substrate material, asphalt coating, top surface granules, and backdust particles. The substrate is a thin porous sheet made of fibers in a nonwoven pattern, which becomes impregnated by asphalt. The asphalt coating, which consists of 35% air blown asphalt and 65% mineral fillers by weight, is heated so that it fully coats and impregnates the fiberglass matting. While still hot, granules are pressed onto the surface so that 100% coverage is achieved. The shingle is then cooled and the back surface is reheated so that backdust dust material will achieve 100% coverage of the backside. Acceptability of the glass cullet modified shingles is based on the Standard Specification for Asphalt Shingles Made from Glass Felt and Surfaced with Mineral Granules (ASTM D3462).

Task 8: Measure the solar reflective properties. The surface reflectance of the prepared shingles were measured by using a spectrophotometer under a controlled light source that simulates natural daylight illumination and under various incident and reflected angles. The reflectance of glass-modified shingles was compared against the reflectance of conventional shingles available in the market. The Solar Reflectance Index (SRI), absorptance, and emittance of the manufactured shingles were measured using ASTM E903, ASTM E1918, ASTM E1980, and ASTM E408. Sample dimensions were 3" x 3" x 1/8". Initial tests included two readings of three replicates. To increase precision, samples with pigments received six readings of three replicates per type.

Task 9: Test the viscosity of asphalt coating blends. To evaluate the workability and consistency of the asphalt coating blends, viscosity measurements were taken using a Brookfield

rotational viscometer according to the procedure outlined by the Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer (ASTM D4402). A relatively low viscosity, 1000 to 5000 centipoise, of the coating blends is desirable to ensure efficient processing (Whitaker, Smith and Puryear 2010, Bondoc, et al. 1988). Figure 5 shows the rotational viscometer and temperature controlled thermal chamber. A testing temperature of 204°C was utilized since it was the minimum mixing and handling temperature needed to produce the laboratory shingles, and it ensured that the blends had enough flow to provide accurate measurements of viscosity.



Figure 5 Rotational Viscometer and Thermal Chamber

The initial asphalt coating blend prepared for viscosity measurements included 100% Air Blown Asphalt with no filler materials. Mineral filler materials were then added to the air blown asphalt at a ratio of 65% mineral fillers to 35% asphalt by weight. The mineral filler material evaluated included green glass, clear glass 1, clear glass 2, and high calcium limestone as the conventional aggregate. Three measurements of each coating blend were completed to achieve an average viscosity.

Task 10: Determine the tear strength. To determine if the shingles achieve minimum performance standards as specified in Standard Specification for Asphalt Shingles Made from Glass Felt and Surfaced with Mineral Granules (ASTM D3462), a pendulum test was used to measure tear strength. As shown in Figure 6, tear strength was determined by using an Elmendorf-type tearing tester (Model: Mechanical Elmendorf Tear, Thwing-Albert). The Standard Test Method for Propagation Tear Resistance of Plastic Film and Thin Sheeting by Pendulum Method (ASTM D1922) will produce an average tear strength using an Elmendorf-type tearing tester. Sample dimensions were 3" x 2 1/2" x 1/8". Two sets of each specimen were prepared so that ten measurements could be made for both machine direction and transverse direction readings.



Figure 6 Mechanical Elmendorf Tear Strength Device

Chapter 2 provides a review of literature associated with this research, and results of each project phase and task are discussed in Chapter 3. The last chapter provides a summary of the results and also includes future recommendations and research ideas.

CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

The urban heat island (UHI) phenomenon is becoming increasingly intense as summertime temperatures rise. In the United States, many cities with a population of 1 million or more people experience an annual mean air temperature of a 1.8–5.4°F (1–3°C) warmer than its surroundings (U.S. Environmental Protection Agency 2014). Heat island effect is caused by the development of the earth's surface, which replaces shade from trees and natural vegetation with highly absorptive construction materials, such as roofs. Exposed and highly absorptive materials used on roofs are a major contributing factor to increasing the heat island effect. Mitigation strategies that may be implemented include increasing tree and vegetative cover, creating green roofs, installing cool roofs, and using cool pavements (U.S. Environmental Protection Agency 2014).

2.2 Roofing Systems

A roof is the uppermost part of a building and provides coverage from the rain, cold, or heat. Typically, there are two parts to a roof: the supporting structure and the outer layer (i.e. roof covering). The supporting structure must be strong enough to withstand high winds, sloped to shed water, and in areas of heavy snow, it must be constructed more rigidly to bear the extra weight (Department of the Army 1995). Roof coverings come in a variety of forms. Commercially available coverings include asphalt shingles, roll roofing, concrete and ceramic tiles, slate, terne metal, wood shingles and shakes, aluminum shingles, built-up roofing, and single-ply systems (Genesis Roofing 2013).

The design and appearance of a roof comes in a multitude of variations, which may depend based upon the intended purpose of the building, the selection of materials, and the

architectural concept. Since the primary purpose of a roof is to protect people and possessions from the weather, then the functionality and purpose of the building may dictate certain design parameters of a roof, such as the amount of insulation or ventilation desired. Another variable in roof design is the selection of materials, and roofing materials can vary greatly based upon local choice concerning necessity, customs, available materials, material cost, and the life span of the roof (Leavell 2006). Additional design factors may include domestic architecture, which considers traditions, aesthetics, stylistics, and sustainability features (i.e. solar energy systems, recycled material, etc.).

2.2.1 Climatic Conditions of Roofs

The roof environment is subject to harsh weathering effects, such as ultraviolet radiation as shown in Figure 7, extreme heat, freezing temperatures, and the subsequent fatigue caused by both sudden and cyclical thermal loads. The surface temperatures of a traditional asphalt roof system may reach temperatures upwards of 160°F degrees on a 90°F degree day, and a metal roof will reach temperatures of 180°F degrees on the same day (Nations Roof 2013).

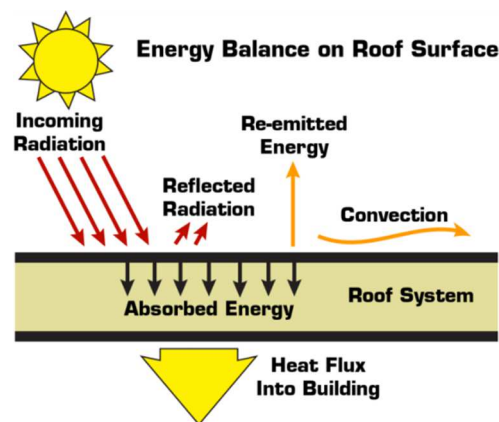


Figure 7 Energy Balance on Roof Surface (ERSystems 2014)

Roof coverings are also exposed to other environmental agents, such as wind, rain, hail, snow, and atmospheric pollution (Kültürä and Türkeri 2012). These environmental factors, as

well as the composition of materials and the materials' ability to resist weathering effects have a direct impact on the performance and life expectancy of a roof. The life span and maintainability of a roof is of utmost importance as the roof is often the least accessible part of a building.

2.2.2 Types of Roofing Systems

Roof systems are generally divided into two generic classifications based on roof pitch: low slope and steep slope. Typical roof slopes are shown in Figure 8, and the slope is considered a primary factor in roof design, since the slope of a roof has an effect on the interior volume of a building, drainage, style, and the material used for the covering (CertainTeed Corporation 2013).

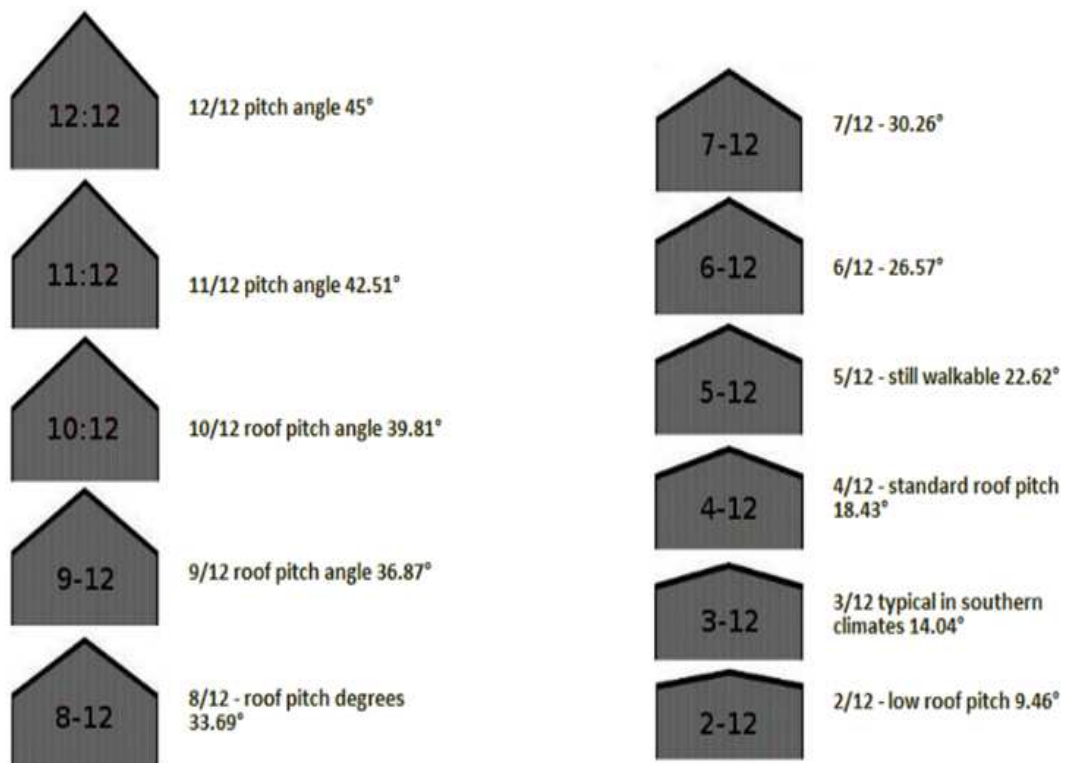


Figure 8 Typical Roof Pitches (APB Pole Barns 2010)

The National Roofing Contractors Association (NRCA) delineates the difference between the two categories at 3:12 (14.04 degrees), whereas low slope roofing is less than or equal to 3:12 and steep slope roofing exceeds 3:12. In contrast, Leadership in Energy &

Environmental Design (LEED) and the Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field (ASTM E1918) defines a low slope roof as being less than or equal to 2:12 (9.46 degrees) and a steep slope roof exceeds 2:12.

2.2.2.1 Low Slope Roofing

Low slope roofing systems are often called flat roofs, which are the most cost efficient roof shape. Low slope roofs are the predominate roof type for commercial buildings and are typically comprised of three interacting components: weatherproofing, reinforcement, and the surface. The weatherproofing component is the most important element because it keeps water from entering a roof assembly, while the reinforcement layer adds strength, puncture resistance, and dimensional stability to the system (National Roofing Contractors Association 2013). The surface layer provides the weatherproofing while the reinforcement layers protect from ultraviolet radiation and precipitation. Enhancements to the surface layer may include benefits, such as increased fire resistance, improved traffic and hail resistance, and increased solar reflectivity (National Roofing Contractors Association 2013).

Classifications of low slope roofing systems include: built-up roof (BUR) membranes, metal roof panels, polymer-modified bitumen sheet membranes, single-ply membranes, and spray polyurethane foam (SPF) based systems (National Roofing Contractors Association 2013). BUR systems are often called tar and gravel roofs, and they consist of built up layers of bitumen (tar or asphalt), reinforcing fabric (felt or ply sheets), and mineral aggregates (gravel or slag). Structural metal roof panels provide excellent water resistance capabilities and can be used for low or steep slope roofs. Single-ply membranes are either thermoplastic or thermoset factory-manufactured membranes that are adhered to the roof surface and do not receive any other surfacing, such as polyvinyl chloride (PVC) or ethylene propylene diene terpolymer (EPDM).

SPF roof systems are constructed by mixing and spraying a two-component liquid that forms the base and then a protective surfacing of an adhered roof system (National Roofing Contractors Association 2013).

2.2.2.2 Steep Slope Roofing

The slope of a roof is often referred to as the pitch, and the primary purpose of pitching a roof is to redirect water and snow. Unlike a low slope roofing system that uses a waterproof membrane to protect the building, steep slope roofs are not watertight and are designed to shed water. Steep roofs act more like a series of umbrellas than a weather-tight skin (Dearborn Real Estate Education 2013). Generally, steeper roofs last longer, and steep roofs are typically more common in areas of high rain or snowfall, since water runs off steep roofs faster and the roof dries faster.

Since most single family homes in the United States are constructed with a pitched roof, steep slope roofing is commonly referred to as residential roofing. Steep slope roofing products are generally more visually appealing because they are critical aesthetic components for residential construction where the roof can consist of 40% of the exterior visual appearance of a home (CertainTeed Corporation 2013). To classify residential roofing slopes more specifically, Table 1 contains common roof slopes and the terms which classify them.

Table 1 Common Residential Roof Slopes (CertainTeed Corporation 2013)

Type of Roof Slope	Pitch
Conventional	< 9:12
Higher Slopes	9:12 - 20:12
Steep Slope	$\geq$ 21:12

Steep slope roof systems consist of three primary components: roof deck, underlayment, and roof covering. The roof deck is the structural component and is typically made out of wood materials such as plywood or oriented strand board (OSB), while the underlayment is a secondary weatherproofing barrier and is usually referred to as felt or paper (National Roofing Contractors Association 2013). The roof covering provides water shedding and ultraviolet protection, and there are six generic classifications roof coverings: asphalt shingles, clay or concrete tile, metal, slate, wood shakes, and synthetic materials. Asphalt shingles are the most widely used roof covering for new home construction and remodeling, and shingles are used on four out of five homes in the United States because of their economic value, durability, and aesthetic appeal (Genesis Roofing 2013).

2.2.3 Asphalt Roofing Products

In the United States, the most popular and economical form of roofing is asphalt products. There are four main categories of asphalt roofing products: asphalt-saturated felt, roll roofing, modified bitumen roofing (MBR), and asphalt shingles (Falkiewicz and Maldonado 2010). The specific application of an asphalt roofing product can vary based upon the budget, the type of surface, the slope of the roof, climatic conditions, installation constraints, and the height of the building.

The most common asphalt roofing product is asphalt shingles and can last from 20 to 50 years (Leavell 2006). Asphalt roof shingles are designed to protect the roof from weathering and have excellent waterproofing capabilities, but as aging occurs, the weathering process causes oils from the asphalt to surface, which causes curling, cracking, and blistering (IKO 2012).

2.2.4 Components of Asphalt Roof Shingles

Asphalt shingles are true composites that are made from a variety of materials, including fiberglass or organic felt, asphalt binder, mineral filler, and aggregate granules. By weight,

shingles may be made of 80% mineral and rock, and despite being called asphalt shingles, asphalt represents a very small yet important element (Leavell 2006). Fiberglass shingles are composed of 19-36% asphalt by weight respectively, 8-40% mineral filler, 20-38% sand-sized mineral granules, and 2-15% fiberglass felt backing (U.S. Environmental Protection Agency 2010). The major components of typical fiberglass roof shingles can be classified as the substrate, asphalt coating with mineral fillers, and aggregate granules interact and ultimately affect performance, life expectancy, and weather resistance.

2.2.4.1 Substrate

The substrate, shown in Figure 9, is typically made of a sheet of fibers in a nonwoven pattern. Specifically, the glass fiber mats used are within the range of about 1.5 to 2.0 lbs/480 ft² (Falkiewicz and Maldonado 2010). One or more layers of thin porous sheets may be used by adhering each together with asphalt coating material in order to increase the overall thickness and weight of the shingle, which ranges from 1.8 to 2.3 lbs/ft². The base is an asphalt impregnated mat with a thickness of about 10 to 35 mils if fiberglass, and if felt about 25 to 95 mils (Bondoc, et al. 1988).

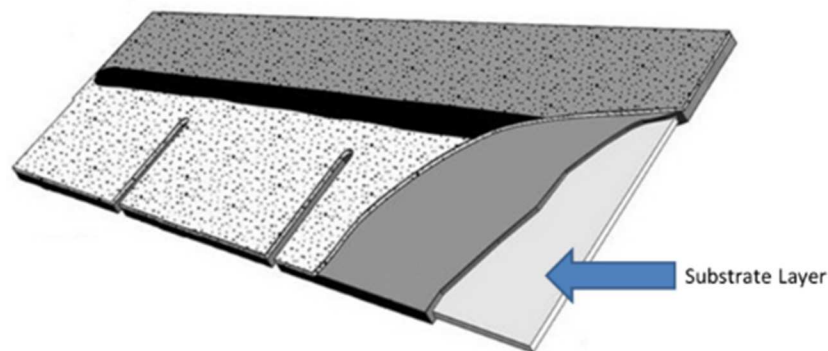


Figure 9 Substrate Layer of a Fiberglass Roof Shingle (Dunlop 2003)

The substrate or support layer is a felted, fibrous layer that is impregnated with a waterproofing agent, such as a bituminous coating that contains finely ground mineral stabilizer.

The felt acts as a carrier, substrate, and preserver of asphalt. The substrate matting when coated by asphalt serves as reinforcement and the structural base of the shingle to which surface granules are applied (IKO 2012).

The substrate may consist of organic or inorganic material. The matting can be made of any substance that reinforces the roofing shingle, such as mineral fibers, cellulose fibers, rag fibers, or synthetic fibers (Leavell, Glass Backdust for Roof Covering 2003). In the past, organic fiber materials, such as rag, wood, paper, or jute fibers were used, but organic materials tend to absorb and release moisture, which results in expansion and contraction causing blisters (Pagen, Stepien, Jr. and Morris 1986). The preferred material for the substrate is a nonwoven web of glass fibers. Though paper matting can be used, the heart of an asphalt shingle is a fiber mat made of nonwoven fiberglass (Leavell 2006). Additionally, fiberglass is preferred due to the heat and hydro stability and fire resistance (Pagen, Stepien, Jr. and Morris 1986).

2.2.4.2 Asphalt Coating with Mineral Fillers

A mineral filled coating is used to impregnate, laminate, and coat the top and bottom surfaces of the substrate material. The mineral filled coating is used to saturate the top and bottom surfaces of the mat, and the weight of the mat will directly vary with the thickness of the applied layer (Leavell 2006).

Asphalt is a suitable coating material for roofing shingles due to its softness, flexibility, and strength (Falkiewicz and Maldonado 2010). Due to its highly viscous nature, high temperatures (250 to 350°F) are required to make the material fluid for the addition of filler material and the production of shingles, but the curing time is fast since the shingles achieve full strength as the material cools. The coating of the base sheet is generally of a viscosity between 1,000 and 5,000 centipoise (Bondoc, et al. 1988).

As shown in Figure 10, the use of mineral fillers extend the asphalt coating and can implement the use of waste material as a way to reduce cost, increase certain performance aspects, and provide environmental benign qualities (Leavell 2006). Mineral fillers can equal up to 68% by weight of the asphalt coating and up to 40% by weight of the entire shingle product. Mineral filler is a major raw material requirement in the majority of manufactured asphalt shingles, and ideal filler should be environmentally benign, economical, non-absorptive, opaque to UV radiation, low free lime content to prevent accelerate granule loss, capable of producing low compound viscosities, increase stabilization of coating, little or no calcium carbonate content, and relatively low specific heat with considerations to its effect on tensile, elongation, pliability, tear resistance, and elasticity properties of the asphalt coating (Shaw 1999).

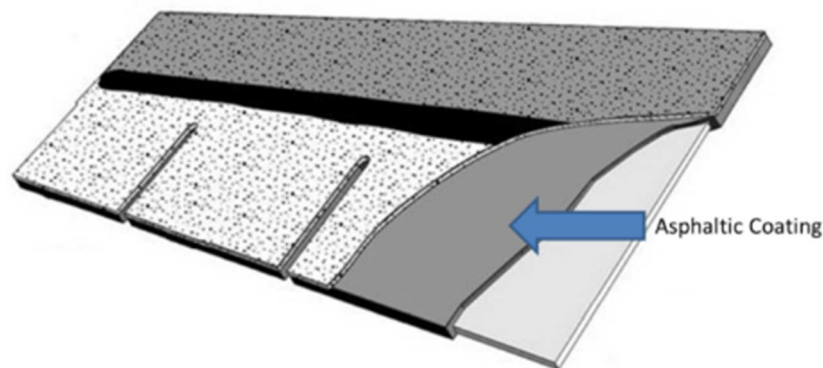


Figure 10 Asphalt Coating of a Fiberglass Roof Shingle (Dunlop 2003)

Examples of filler material include fly ash, recycled rubber, recycled shingles, fine grained carbonate rock, dolomite, limestone, trap rock, sand, and stone dust. Limestone has dominated the market due to its naturally occurring abundance, satisfactory performance, and positive reactions with asphalt as it does not make it brittle or loose granules (Leavell 2006). It possesses a specific gravity of 2.65, which is ideal for weight loadings and viscosity. Other effects on viscosity attributed to the filler are shape in which limestone is blocky and irregular

and size distribution, in which limestone has a median diameter is 34.22 microns (0.0013 inches) (Leavell 2006).

However, no single gradation has been established by industry. A standard of 60-80% of the material passing a No. 200 mesh is typical (Leavell 2006). Similarly, Falkiewicz & Maldonado (2010) state that mineral fillers should be between 75-90% smaller than the No. 200 mesh, and they should be concentrated at 50-70% by weight of the total formulation. Pagen, Stepien, Jr., & Morris (1986) determined a preferred coating formulation for inorganic fiber mat based bituminous roofing shingles, which includes 3.2% elastomeric polymer, 39.3% bituminous composition, 57.5% trap rock dust stabilizer. Using recycled rubber, the formula is 3.2% elastomeric polymer, 37.2% bituminous composition, 57.5% mineral stabilizer, and 2.1% recycled rubber. Reclaimed rubber is a more cost effective option than polymer modifiers, and it improves the durability of asphalt and resistance to ultraviolet radiation (Pagen, Stepien, Jr. and Morris 1986).

2.2.4.3 Aggregate Granules

While still in its plastic state, the mineral filled coating bitumen receives embedded granules that are opaque to ultraviolet radiation (Pagen, Stepien, Jr. and Morris 1986). Before cooling, granules are pressed into the asphalt surface for ultraviolet radiation protection (IKO 2012). As shown in Figure 11, there are three categories of aggregate granules: prime, headlap, and backdust. Prime and headlap granules are referred to as top surface granules, but the difference is that prime granules are typically color coated, and headlap granules are not due to the expense of ceramic color coating. Top surface granules are pressed onto the weather exposed face for protection from the sun and as a decorative coating. Backdust particles are applied to the underside of the asphalt shingle.

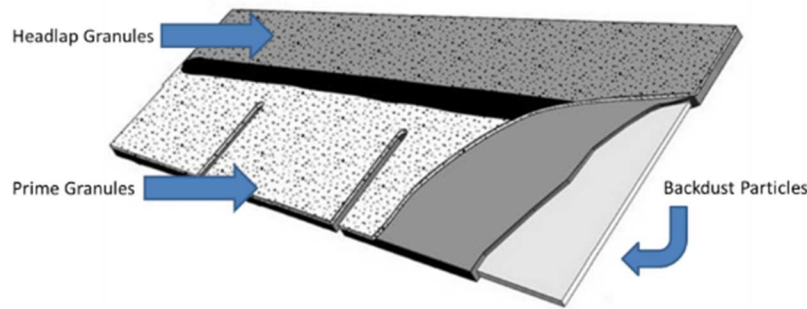


Figure 11 Aggregate Granules of a Fiberglass Roof Shingle (Dunlop 2003)

The top surface granules represent the greatest expense to manufacturers, particularly the ceramic coated prime granules (Leavell 2006). Top surface granules provide weight and ultraviolet protection due to its opaque features. Without this, bitumen may crack, deteriorate, and permit water penetration (Pagen, Stepien, Jr. and Morris 1986). In humid climates, up to 10% of granules may be replaced by a special algae-resistant material, which includes copper oxide, to prevent premature discoloration (Leavell 2006).

Materials consist of rock granules coated with colored ceramic for the prime granules, and then rock or slag granules with similar gradation for the headlap granules. Ideal top surface materials are either igneous or metamorphic, inherently opaque, and must be resistant to multiple heat-thaw cycles. The granules most widely used are crushed slate, basalt, and trap rock (Pagen, Stepien, Jr. and Morris 1986). Fine grained rocks with minimal mineral cleavage when crushed are preferred, and prime and headlap granules should meet the same gradation and should meet American Society for Testing and Materials #11 narrow distribution, which resembles coarse sand from the 12x40 U.S. Sieve Series mesh (Leavell 2006). The top surface layer includes decorative and protective mineral roofing shingle granules from #5 to about #30 (Leavell 2003). Headlap granules consists between 0.2 mm and 2 mm, and prime granules are the exposed color coated roofing granules, which typically are relatively higher in cost (Leavell 2003).

Backdust is a fine particulate material on the back surface of a roofing shingle that prevents the shingles from sticking together when stacked or rolled (Leavell 2003). The backdust particles isolate the hot asphalt in order to prevent shingles from sticking together when packaged. The backdust carries mineral material which is non-cementitious, such as mica flakes, talc, sand, and the like (Bondoc, et al. 1988).

Finer silt-sized granules are used as backdust, and materials may include talc, crushed carbonate, igneous and metamorphic rock fines, crushed glass, slag, and sedimentary silica sand (Leavell 2003). The typical particle size is similar to fine grained sand between 0.04-0.30mm, and the gradations are sufficiently fine sand size without significant fines (less than 5-10% of 200 mesh), with a target gradation of 50x200 on the U.S. Standard Sieves (Leavell 2003).

2.2.5 Manufacturing Asphalt Roof Shingles

The manufacturing process of asphalt roof shingles is the same for both organic and inorganic shingles, and it can be completed in six basic steps: felt saturation, coating, mineral surfacing, cooling and drying, formatting/product finishing, and packaging (Falkiewicz and Maldonado 2010). As shown in Figure 12 and Figure 13, shingles are produced by passing the base material through a machine that successively adds the other components (Made How 2013).

Organic felt or fiberglass matting first starts by being fed into a dry looper, and then the material is passed through a pre-saturation chamber to be sprayed with hot asphalt to remove any moisture and into a saturation tank for soaking and the filling of all voids (Poole 2011). Felt saturation involves saturating the substrate matting material with a low softening point asphalt. Asphalt used to manufacture shingles is not in the same state as asphalt used in pavements. Shingle asphalt must be oxidized to cause a chemical reaction, which softens the asphalt in order to produce a good shingle (Poole 2011).

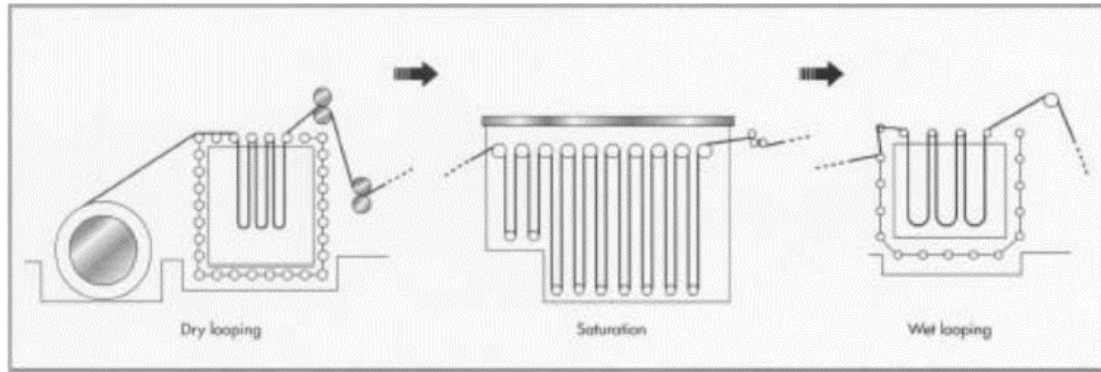


Figure 12 Dry Looping, Saturation, and Wet Looping (Made How 2013)

Following felt saturation is the coating process, which is the application of the modified asphalt coating which includes mineral fillers. The substrate matting is coated on both sides between two coating rollers. Mineral fillers are added to the asphalt to increase durability. While still hot, granules are then applied during the mineral surfacing stage as shown in Figure 13, and then the sample is allowed to cool and dry to the ambient temperature. Passing through a series of rollers, granules are embedded to the top surface of the asphalt-coated mat, and a coating of fine particles of a mineral is applied to the back surface of the mat (Made How 2013).

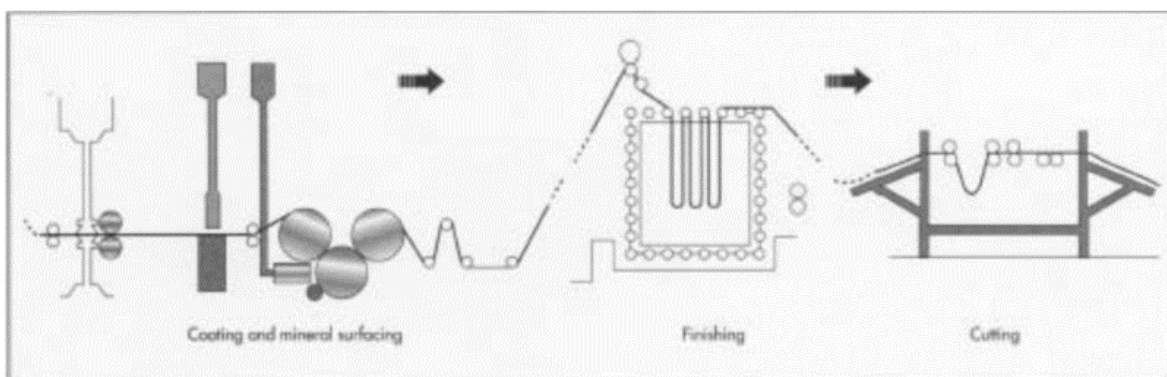


Figure 13 Coating, Surfacing, Finishing, and Cutting (Made How 2013)

The material passes through a cooling loop and then into a cutting machine to be cut from the backside into the desired size and shape (Made How 2013). The asphalt product is formatted (e.g. rolled or cut) to specific size prior to packaging the finished product (Falkiewicz

and Maldonado 2010). The cut asphalt shingles are stacked into bundles, wrapped, and labeled for sale (Poole 2011).

2.3 Heat Island Effect

Urban heat islands (UHI) exist when temperatures in urban areas are significantly higher than surrounding suburban and rural areas. UHI is a climatic phenomenon that has an important energy and environmental impact on the urban environment, and observations in Athens have shown air temperatures of more than 10°C warmer than their surrounding rural areas and an increase of up to 70°C on roofing surfaces (Vardoulakis, et al. 2011).

2.3.1 Consequences of Heat Island Effect

UHI has a multitude of negative consequences on communities, such as increased energy consumption, elevated emissions of air pollutants and greenhouse gases, compromised human health, and impaired water quality (U.S. Environmental Protection Agency 2014). In summer, air-conditioning is used for indoor thermal comfort, which increases energy consumption, peak energy demand, and energy costs, and where air-conditioning is not used, there is discomfort and even death, as occurred in the Chicago heat wave of 1995 (Bretz, Akbari and Rosenfeld 1997).

High air temperatures have been linked to increased air pollution, such as the accelerated formation of smog. In Los Angeles, eliminating the 3°C (7°F) heat island will lower the average air temperature to 22°C (71°F) and may greatly reduce smog episodes (Bretz, Akbari and Rosenfeld 1997). Additionally, the increased use of summertime air-conditioning results in emissions of air pollutants, such as carbon dioxide and nitrogen oxides.

2.3.2 Heat Island Mitigation Strategies

A major factor contributing to the formation of heat islands are the thermal properties of the materials used in urban environments. Particularly, dark colored surfaces absorb solar radiation

during daytime and reradiate it during the night. Pavements and roofs, which make up a major part of urban surfaces, are a replacement for natural vegetation and have a reduced potential to decrease ambient temperature through evapotranspiration and shading (Synnefa, Santamouris and Livada 2006). An aerial study of the composition of Sacramento metropolitan area found land use as 28% rooftop, 16% streets, and 14% other impervious surfaces, such as parking lots, driveways, and sidewalks, with an overall potential for modifying 18% of the urban albedo in Sacramento (Bretz, Akbari and Rosenfeld 1997).

According to the United States Environmental Protection Agency's (EPA) Heat Island Reduction Program, the major strategies and technologies to mitigate urban heat island effects include: trees and vegetation, green roofs, cool roofs, and cool pavements. In order to alleviate the UHI adverse effects, several techniques have been proposed like reducing emissions, increasing green spaces, using cool materials as construction and roof materials, photovoltaic canopies, and super-hydrophilic photo catalyst-coated building surfaces with water film (Vardoulakis, et al. 2011).

2.3.2.1 Trees and vegetative cover

A simple and cost effective method to reducing heat island effect is to provide trees and other vegetation to urban areas, which provide shade and evapotranspiration. A study of two houses in Sacramento during the summer of 1992 showed that shaded surfaces may be 20–45°F (11–25°C) cooler than the peak temperatures of surfaces without shade (Akbari, Kurn, et al. 1997).

When strategically planted around buildings, parking lots, and streets, then benefits to communities include reduced energy use, improved air quality, lower emissions, improved stormwater quantity and quality management, reduced pavement maintenance (U.S. Environmental Protection Agency 2014). Additionally, evapotranspiration, which is the

combination of evaporation and transpiration, is shown in Figure 14 and can help reduce peak summer temperatures of up to 9°F (5°C) (Kurn, et al. 1994).

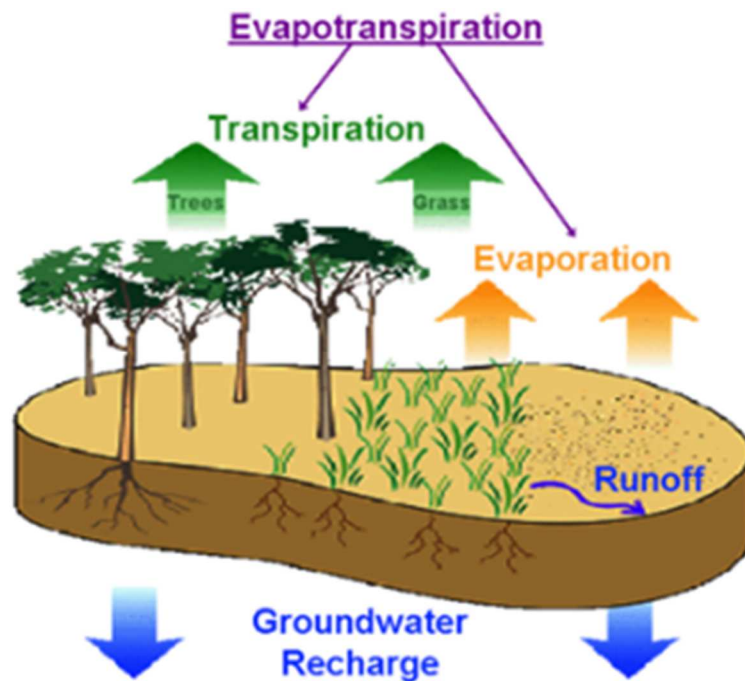


Figure 14 Evapotranspiration (Tsun 2003)

Trees and vegetation can also improve quality of life because of their aesthetic value and noise reduction capabilities. Although costs associated with planting trees and vegetation may include the initial purchase, planting, and maintenance, the benefits of urban forestry are almost always higher than the costs (U.S. Environmental Protection Agency 2014). In 2005, a study of five cities in the United States found that for every dollar invested in the management of urban forestry, the benefits returned annually ranged from \$1.37 to \$3.09 (McPherson, et al. 2005).

2.3.2.2 Cool Roofs

Cool roofing products are best suited for hot climates and can be used on urban surfaces to cost-effectively reduce cooling energy use, improve air quality, and decrease greenhouse gas (GHG) emissions from urban areas where roofs constitute a major part of exposed surfaces (Xu, et al. 2012). Therefore, it is best to use cool roof coverings that have high solar reflectance and high

infrared emittance in order to contribute to heat island mitigation (Kültür and Türkeri 2012). Commercially available cool materials for roofs include cool roof coatings (elastomeric, acrylic, etc.), cool single ply membranes, reflective tiles, metal roofs, and the use of cool colors (Synnefa, Santamouris and Livada 2006). A white basecoat and cool color topcoat applied to asphalt shingle granules achieved reflectance values as high as 0.45 when the granules were covered (Levinson, Berdahl, et al. 2007).

Roofs with high albedo significantly lower surface temperatures and reduce heat flux through the building envelope as compared low albedo surfaces. During peak summer weather, high solar reflectance and emissive materials can remain 50-60°F (28-33°C) cooler than traditional materials (Konopacki and Akbari 2001). With a surface reflectance change from 0.1 (black roof) to 0.7 (white roof), an energy savings of 46-50 kWh/day per 700 m² was achieved, which represents a 14-26% energy savings (Synnefa, Santamouris and Livada 2006).

For roofing materials to be regarded as cool, the solar reflectance must exceed a specified threshold, which for an asphalt shingled, sloped roof is typically 0.25 (Berdahl, Akbari, et al. 2012). Cool roofing alternatives as opposed to conventional roofing materials are usually available at nominal initial costs and lower life-cycle costs because of potential longer life expectancy and energy savings (Bretz, Akbari and Rosenfeld 1997).

2.3.2.3 Green Roofs

Green roofs (i.e. rooftop gardens, eco-roofs, vegetated roofs, etc.) contribute to heat island mitigation by providing shade to reduce surface and air temperatures and enhancing the evapotranspiration process. Surface temperatures of green roofs can actually be cooler than the air temperature during the summer, compared to temperatures of a conventional roof which may be 90°F (50°C) warmer than ambient (U.S. Environmental Protection Agency 2014). As shown

in Figure 15, the four main components of a green roof include water proofing membrane and filter membranes, drainage films, growing medium, and vegetation (Saadatian, et al. 2013).

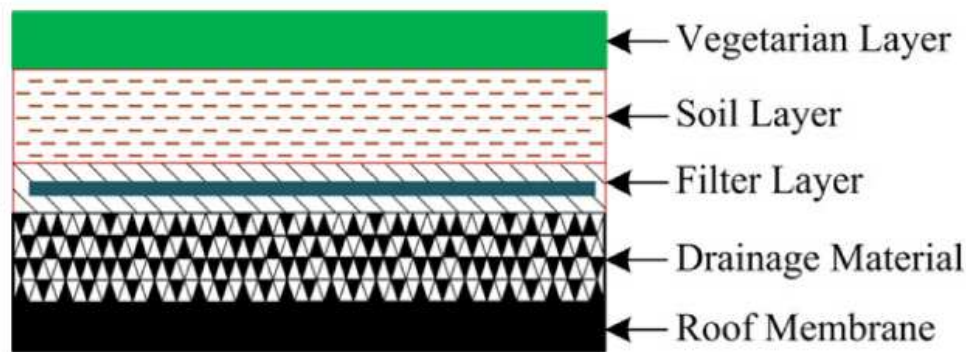


Figure 15 Components of a Green Roof (Saadatian, et al. 2013)

Green roofs can be implemented on buildings from industrial facilities to private residences, and they can be as simple as a 2-inch vegetated covering or as complex as a fully accessible park complete with trees (U.S. Environmental Protection Agency 2014). Although the initial cost of green roofs is more than three to six times of the conventional roofs, green roof savings are in the form of stormwater and energy efficiency (Saadatian, et al. 2013). Benefits of green roofs include the reduction of energy consumption needed to provide cooling and heating, improved air quality, decreased greenhouse gas emissions, enhanced stormwater quantity and quality management, improved quality of life, and improved thermal comfort (U.S. Environmental Protection Agency 2014).

2.3.2.4 Cool Pavements

Cool materials for the urban environment could be roughly divided into two categories: cool materials for buildings and cool paving materials. The term cool pavement applies to materials that aim to reduce heat island effect by reflecting more solar energy or increase more water evaporation than conventional pavements (U.S. Environmental Protection Agency 2014).

Conventional paving materials can reach peak summertime temperatures of 120–150°F (48–67°C), transferring excess heat to the air above them and heating stormwater as it runs off the pavement into local waterways (U.S. Environmental Protection Agency 2014). Pavements in urban areas comprise of approximately 30–45% of land cover based on an analysis of four geographically diverse cities and are an important element to consider in heat island mitigation. (Akbari, Rose and Taha 1999).

An increase in pavement albedo reduces surface and atmospheric temperatures, reduces the convection of heat, decreases cooling energy demand, and slows the formation of urban smog (Levinson and Akbari 2002). Benefits of effective cool pavements to communities include enhanced stormwater quantity and quality management, lower tire noise, enhanced safety, better nighttime visibility, and improved thermal comfort (U.S. Environmental Protection Agency 2014).

2.3.2.5 Mitigation Strategies Conclusion

The consequences of UHI effect are becoming increasingly severe, such as the increase in energy consumption, higher cooling demands, poor air quality, increased emissions, smog, thermal discomfort, and health effects. For these reasons, there has been an impetus in research aiming to understand the origin of UHI and to develop mitigation measures (Vardoulakis, et al. 2011). Despite the initial costs, alternatives that contribute to heat island mitigation may be cost-effective in terms of life cycle costs.

2.4 Sustainable Materials Management (SMM)

The United States Environmental Protection Agency's Sustainable Materials Management (SMM) Program promotes the use and reuse of sustainable materials throughout a product's life cycle, to include recycling, composting, energy recovery, and landfilling. This approach aims to

conserve natural resources, reduce waste, and minimize environmental impacts (U.S. Environmental Protection Agency 2013).

The SMM applies to both consumer's in their everyday lives as well as industrial supply chains, such as by products from coal combustion, foundry sand, iron and steel slag, and scrap tires. Materials such as scrap tires, glass, and roofing shingles are being implemented into highway construction (Maupin 1998). The benefits of reducing and reusing materials include the conservation of landfill space, and the reduction of the need to produce new materials from virgin resources resulting in economic and environmental benefits (U.S. Environmental Protection Agency 2013).

2.4.1 Construction and Demolition (C&D) Materials

Wastes materials generated from the construction industry's supply chain are referred to Construction and Demolition (C&D) and are a result of new construction, renovation, or demolition projects. C&D waste may end up municipal solid waste (MSW) landfills, C&D landfills, combustion facilities, or unpermitted landfills (U.S. Environmental Protection Agency 2013). MSW landfills are designed to dispose household waste while C&D landfills are exclusively for C&D materials, and less landfill waste reduces methane gas emissions which contribute to global climate change (U.S. Environmental Protection Agency 2013).

C&D materials may include concrete, wood, drywall, bricks, metals, glass, plastics, and salvaged components from buildings, roads, and bridges, and the three largest components include concrete, wood, and drywall (Sandler 2003). Concrete is the most dominant consisting of 40-50% of debris generated annually due to its high volume usage in infrastructure, buildings, and civil engineering applications (Sandler 2003). Primarily due to residential construction, estimates of wood debris produced annually is approximately 35.1 million tons, which comprises

of 20-30% of C&D debris (Sandler 2003). Drywall debris continues to increase due to its prevalence as a finished interior in new residential construction and renovations.

2.4.2 Recycled Glass

Glass is comprised of all natural resources that are melted together, such as silica sand, soda ash, limestone, glass cullet, and substances to change the color. For over 400 years, glass has been deemed as a safe food and beverage packaging material in the United States (Glass Packaging Institute 2010). Because of its durability, other postconsumer sources of glass include furniture, appliances, electronics, and non-food containers, and C&D sources of glass include windows, mirrors, and lights.

According to the Glass Packaging Institute, approximately 13 million tons of glass waste are generated annually, and food, soft drink, beer, food, wine, and liquor containers make up over 90% of this amount with the remaining 10% coming from cookware, glassware, and home furnishings (Glass Packaging Institute 2010). A study of waste glass from large cities across the world determined that about 3-5% of all household waste was from glass (Wu, Yang and Xue 2004). However, in the United States, the national glass container recycling rate is 28% as of 2008 (Glass Packaging Institute 2010).

The market for the use of recycled glass is primarily with the glass container industry, as ninety percent of recycled glass is used to create new containers (Glass Packaging Institute 2013). Recycled glass can also be used in kitchen tiles, counter tops, and wall insulation. Many non-container uses of glass cullet include building material applications, concrete aggregates and additives, construction aggregate, sand blasting, insulation, paving, art glass, and miscellaneous applications such as filters, landscaping, reflective beads, tableware, hydraulic cement, polymer deposits, and jewelry (Reindl 2003).

However, due to impurities, shipping costs, and mixed color sources, the use of waste glass, which has a subangular particle shape and a smooth, flat surface texture in construction materials is a productive alternative (Polley, Cramer and de la Cruz 1998). Major construction applications include a partial replacement for aggregate in asphalt concrete, as fine aggregate in unbound base course, pipe bedding, landfill gas venting systems, and as gravel backfill for drains (Shi and Zheng 2007). Reddy (1999) concluded that glass cullet was a feasible alternative backfill material for retaining structures.

The use of recycled materials as alternatives in Portland cement concrete (PCC) is well documented (Huang, Shu and Li 2005). As a fine aggregate, glass cullet below 30% is practical along with usage admixtures to obtain desired workability and air content values (Park, Lee and Kim 2004). Glass powder as a replacement to cement of up to 30% was also deemed feasible (Shayan and Xu 2004). In producing self-compacting concrete (SCC), glass cullet is also a feasible substitute to replace up to 30% fine aggregate and 15% coarse aggregate with the use of fly ash to suppress the alkali-silica reaction potential (Kou and Poon 2009). As a replacement to sand in mortar, glass increased durability but also increased the likelihood of micro-cracking and being potentially deleterious to alkali-silica reaction (Tan and Du 2013).

Glass can be recycled over and over again and has the potential to be reused in a wide variety of applications. Glass recycling increased from 750,000 tons in 1980 to more than three million tons in 2011 and using glass cullet has the potential to save money and help the environment (Glass Packaging Institute 2013).

2.5 Building Energy Management

The building envelope is the physical component that acts as a barrier between external environmental conditions and the interior space of a building. According to the Whole Building

Design Guide (WBDG), components of building envelopes include below grade construction, exterior structural and nonstructural walls, fenestration (windows, door, and other openings), roof systems, and atria. Functional aspects of a building envelope must include structural considerations, water and air resistance, condensation, sound transmission, fire safety, security, maintainability, constructability, durability, aesthetics, economics, and last but not least energy conservation (National Institute of Building Sciences 2009).

The building envelope must resist solar heat gain, conduction heat transmission, and infiltration heat transmission, and building energy consumption is a result of the demands of heating, cooling, lighting, hot water, appliances, and electronics, and energy conservation is increasingly important because of its environmental impacts and rising energy costs (Kibert 2008). According the Department of Energy (DOE), buildings consume more energy than any other sector of the U.S. economy, which includes transportation and industry. Becoming energy efficient is a low cost way to save money, and a 20% reduction of energy use in U.S. buildings would result in \$80 billion in savings on the \$400 billion spent annually on energy bills (U.S. Department of Energy 2014). To spearhead the efforts, further DOE research efforts are aimed at developing cost-effective and energy efficient materials and technologies in foundations, insulation, roofing and attics, and walls.

Akbari, Konopacki, and Pomerantz (1999) performed an energy simulation program for 11 U.S. metropolitan statistical areas in a variety of climates evaluated the energy savings during the summer based on an increase in albedo from 0.25 for all buildings to 0.30 for residences and 0.45 for commercial buildings. Utilizing local municipality rates for the price of electricity and natural gas, the sum total results for all 11 MSAs are 2.6 terawatt hours in annual electricity savings, \$194M in net annual savings, and 1.7 gigawatt in peak electricity demand savings. The

entire United States' savings is estimated annually at 10 TWh and \$750M with peak electricity power savings at about 7 GW, which at peak demand would result in the avoidance of 13 power plants at 0.5 GW capacity (Akbari, Konopacki and Pomerantz 1999).

When minimal or no insulation is present in a roofing system and when surface albedo is low, then roof heating loads are maximized, making heat gain a dominant component of the total cooling load of a building. Using insulation with an R-30 value, Simpson and McPherson (1997) measured reductions in daily total load and hourly peak electrical use for air conditioning by 5% by changing from gray shingles (albedo 0.30) to white shingles (albedo 0.75). When ceiling insulation was removed, the air-conditioning reductions from a brown to white was 18% peak load and 28% total (Simpson and McPherson 1997).

Solar reflective materials maintain low surface temperatures in sunlight and have direct effects on cooling energy consumption by increasing the exterior albedo and reducing heat transfer through the building envelope. Through the use of reflective roofs in Florida, experiments on various building types have resulted in a cooling cost energy savings of 19% and a reduction in peak demand of 22% by changing albedo from 0.20 to 0.66 (Parker and Barkaszi, Jr. 1997). In Sacramento, savings of 35% was the result of coating a metal roof with high albedo white paint on a bungalow style school (Akbari, Bretz, et al. 1997).

A study in California showed that cool roof premiums that range between \$0.18–0.20 per ft² are found to be cost effective based upon cooling energy consumption, heating or gas consumption, net energy savings, cost savings from downsizing cooling equipment, and the cost premium for a cool roof (Levinson, Akbari and Konopacki, et al. 2005). Konopacki and Akbari (2001) listed the benefits of whitening a black rubber roof membrane of a large single story retail store in Austin from 5% to 83%, which included an 11% or \$25 average summertime daily

energy savings, a reduced peak demand by 14%, and an annual abated energy expenditures of \$7200 or 7.2 ¢/ft². On the residential scale, an increase in 0.30 reflectance on a 1400 ft² residence in Miami can result in daily savings of 5.9 Wh/ft² or 15% and a reduced peak demand of 0.32 W/ft² or 16% (Konopacki and Akbari 2001). Cooling cost savings associated with a change a roof with higher solar reflectance typically exceeds the heating cost penalty, and increasing roof reflectance can lower energy consumption and the size of heating or cooling equipment needed (MacDonald, et al. 1989).

Increasing building energy efficiency can significantly lower costs and reduce pollution. The impact of whitening a previously black roof in a metropolitan area was a 14-26% energy use reduction and a direct reduction in CO₂ of 11-12 kg CO₂/m² of flat roof area (Xu, et al. 2012). Additional benefits include higher levels of comfort, impacts to the national economy, improvement of energy security, and the protection of the environment (U.S. Department of Energy 2014).

CHAPTER 3 – EVALUATION OF RECYCLED GLASS CULLET AND GLASS MODIFIED FIBERGLASS ROOFING SHINGLES

3.1 Introduction

With the gradual depletion of natural resources and the increase in energy prices, there is a critical need to preserve energy in construction activities and to implement methods that could be environmentally friendly, as well as useful to the industry and the consumers. The United States Environmental Protection Agency (EPA) estimates that 11.5 to 12.8 million tons of glass waste are generated every year with only 38% being recovered in various recycling activities (Reddy 1999, U.S. Environmental Protection Agency 2013). Most of recycling glass activities focus on using glass cullet in the manufacturing of food and beverage containers for re-melt and remold applications. Glass cullet originates from food containers, broken glassware, light bulbs, waste of bottles, and others (Reindl 2003). Recent estimates indicate that every metric ton of recycled glass reduces production of carbon dioxide by as much as 315 kilograms during production of new glass (U.S. Environmental Protection Agency 2013).

With the continuous consumption of energy from non-renewable sources, many cities world-wide with a population that equals or exceeds 1 million people experience an increase in annual mean air temperature of 1-3°C when compared to its surroundings. Further, evenings can experience a difference as high as 12°C (U.S. Environmental Protection Agency 2014). This phenomenon is known as heat island effect. It is becoming increasingly intense as summertime temperatures rise due to global warming. Exposed and highly absorptive materials used on roofs are a major contributing factor to increasing the heat island effect. Roofs collect energy from the sun throughout the day, which results in higher temperatures on adjacent surfaces. In order to mitigate heat island effect, provide thermal comfort, reduce energy demand, and add aesthetic value to the environment, communities can implement a variety of sustainable strategies:

increasing tree and vegetative cover, building green roofs, using cool roofs, and constructing cool pavements (U.S. Environmental Protection Agency 2014). Since approximately 20% of the urban surfaces have roofs, use of cool roofing materials has a great potential to help alleviate urban heat islands, reduce energy consumption, and decelerate global warming (Vardoulakis, et al. 2011). With the need to recycle glass, there is a strong potential to reduce glass waste while attempting to reduce thermal loading on buildings, as well as alleviate heat island effect.

The objective of this study was to evaluate the feasibility of integrating recycled glass cullet in the manufacturing of fiberglass roof shingles and to investigate the interactions that occur when recycled glass cullet is blended with traditional roofing materials. The impact of diverting materials from disposal and reusing Construction and Demolition (C&D) materials includes reduced extraction and consumption of virgin resources. Glass food and beverage containers can be recycled endlessly, and economic benefits of the reuse of glass include: cullet cost less than raw materials, reduces energy demand, prolongs furnace life, and creates 8 jobs for every 1,000 tons recycled (Glass Packaging Institute 2013). Environmentally, benefits include the reduction of emissions, energy consumption, consumption of raw materials, and waste ending in landfills. For every six tons of recycled container glass used, a ton of carbon dioxide, a greenhouse gas, is reduced (Glass Packaging Institute 2013).

3.2 Background

3.2.1 Recycling Practices of Glass Cullet

Recycling of glass cullet can be categorized into two main groups: (1) new glass and bottle containers; and (2) other applications. Secondary recycling applications are categorized into eight main groups (Reindl 2003): (1) building materials; (2) concrete production; (3) construction aggregates; (4) industrial mineral uses; (5) building insulation; (6) asphalt paving;

(7) remelt; and (8) others. While the recycling of glass cullet is beneficial in most applications, the performance of the product should not be compromised as compared to products prepared with virgin materials. Numerous advantages can result from the recycling of glass cullet: (1) reduced emissions and energy consumption during processing and manufacturing of virgin materials; (2) reduced consumption of virgin materials; (3) diminished consternation of public concerning emissions; (4) improved economic competitiveness of construction and manufacturing; and (5) reduced glass cullet disposed in landfills.

Research studies conducted on the use of glass cullet in secondary applications showed promising results. Glass-asphalt (glasphalt) has been used since the 1960s with a content of glass cullet ranging from 10 to 15% (Arabani 2011). Given its high reflectivity especially at night, the use of glass cullet was reported to improve driving conditions and to provide less hazardous driving. In addition, the use of glass cullet improved frictional resistance due to the angularity of glass particles and the mix fracture strength. However, given their high silica content, glass-asphalt is more susceptible to moisture damage but is less susceptible to temperature changes in comparison to regular asphalt mixes. A study was conducted to evaluate the use of glass cullet in the production of glass-ceramics in combination with fly ashes and steel slags (Karamberi, Orkopoulos and Moutsatsou 2007). Ten sources of glass cullet were tested by melting at 1450°C. Produced mixes were evaluated using x-ray diffraction and scanning electron microscopy. A study examined the chemical reactions taking place when glass cullet is used as a partial cement replacement in concrete (Dyer and Dhir 2001). It was reported that given its high content of sodium and silicon, glass cullet can cause harm to concrete through the alkali-silica reaction. However, this failure mechanism can be avoided by including pozzolans in the concrete mix design.

3.2.2 Asphalt Roofing Shingles

Asphalt roofing products are a common roofing application in the United States given their economic competitiveness and ease of installation. The most common asphalt roofing product is asphalt shingles, which account for approximately 85% of roofing products used in the residential sector of the United States (Leavell 2006). A fiberglass roofing shingle is comprised of four major components: a substrate, asphaltic coating with mineral fillers, surface granules, and backdust. To produce conventional shingles, fibrous matting serves as the substrate and becomes impregnated by asphalt. The asphaltic coating, which includes mineral filler material, is heated so that it fully coats and impregnates the fiberglass matting. Then, the roofing granules are pressed onto the top surface prior to cooling to provide the finished appearance so that 100% coverage is achieved. The shingle is then cooled, and the back surface is reheated so that the backdust dust material when applied will achieve 100% coverage of the backside.

Conventional materials used to produce shingles include fiberglass matting as the substrate, air-blown asphalt as the coating material, and aggregates. Aggregates are classified by particle size as top surface granules, filler material, or backdust particles. Typical particle sizes are listed in Table 2.

Table 2 Typical Particles Size Usage on Roofing Shingles

Shingle Component	Particle Size Range	U.S. Standard Sieve
Top Surface Granules	2.36mm - 595 μ m	Mesh #8 - #30
Backdust Particles	595 μ m - 75 μ m	Mesh #30 - #200
Mineral Filler Material	150 μ m - 45 μ m	Mesh #100 - #325

Materials most widely used as top surface granules include crushed slate, basalt, and trap rock (Pagen, Stepien, Jr. and Morris 1986). Finer silt-sized granules are used as backdust, and ideal materials are non-cementitious minerals, such as mica flakes, talc, or sand (Bondoc, et al.

1988). Examples of filler material include fly ash, recycled rubber, recycled shingles, fine grained carbonate rock, dolomite, trap rock, sand, stone dust, and limestone. Limestone has dominated the market due to its naturally occurring abundance, satisfactory performance, and positive reactions with asphalt as it does not make it brittle or loose granules (Leavell 2006).

3.2.3 Heat Island Effect

Urban heat island (UHI) occurs when temperatures in urban areas become significantly higher than their surrounding areas. UHI is a climatic occurrence that has a vital impact on energy consumption and the environment in urban areas (Kültür and Türkeri 2012). Figure 16 displays day and night temperature differences between rural and urban areas, which may be attributed to UHI as well as the cooling effect that parks, open land, and bodies of water have on rural areas (U.S. Environmental Protection Agency 2014). Research shows that many cities around the world have average daytime air temperatures during the summer 5.6°C warmer than their surrounding undeveloped areas (Synnefa, Santamouris and Livada 2006).

The primary cause of heat island effect is urbanization, which causes city-scale climate modification as a result of the development of the earth's surface and the removal of natural vegetation. Heat transfer from absorptive surfaces and the radiation of buildings contribute to heat island effect, and the removal of natural vegetation reduces shading and evaporative cooling (Bretz, Akbari and Rosenfeld 1997). Heat island effect is caused by the use of high solar radiation absorbing materials and the lack of green surfaces (Kültür and Türkeri 2012). UHI is becoming increasingly more problematic in urban areas and is changing the microclimate in those areas. During the summertime, increasing temperatures will increase the surface temperatures of building envelopes, surfaces, and infrastructures, which results in an intensified UHI effect (Xu, et al. 2012).

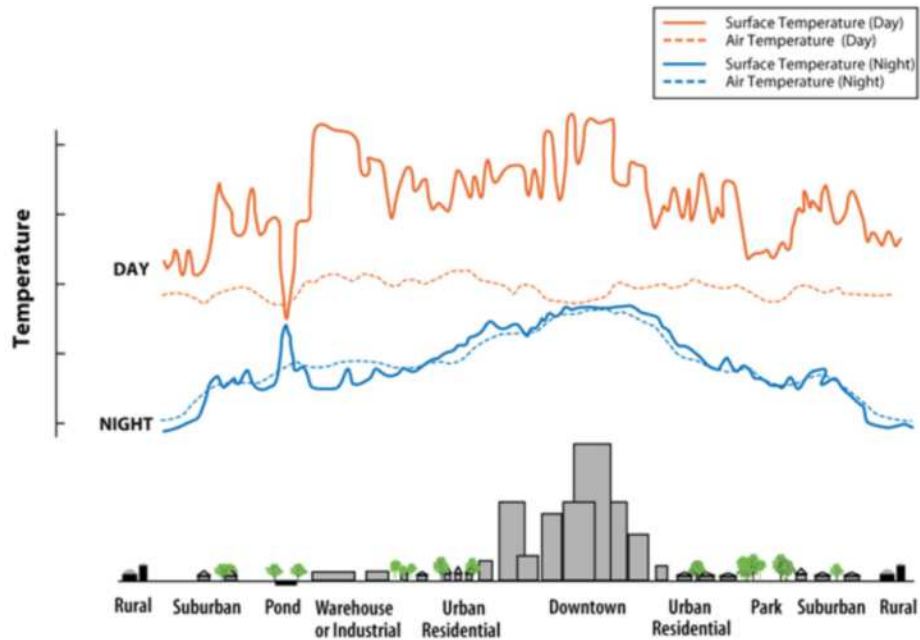


Figure 16 Heat Island Temperature Variance (U.S. Environmental Protection Agency 2014)

3.3 Experimental Program

The objective of the experimental program was to evaluate the suitability of incorporating recycled glass into the manufacturing process of asphalt roofing shingles and to test the hypothesis that the use of recycled glass will increase solar reflective properties without affecting performance of asphalt roof shingles. Table 3 provides an overview of the experimental conditions, variables, and properties testing.

The experimental program was divided in two phases. The first phase of the experimental program was to characterize the engineering properties of glass cullet in comparison to conventional materials used in producing fiberglass shingles. The engineering properties of interest included particle size distribution, specific gravity, absorption, void content, and soundness. The second phase consisted of preparing laboratory shingles in order to measure and compare the solar reflective properties and strength performance of conventional and recycled glass roof shingles.

Table 3 Description of the Experimental Program

Variable	Number of Levels	Description
Type of Aggregate Location: Top Surface Granules	4	Green Glass
		Clear Glass #1
		Clear Glass #2
		Conventional Materials
Usage of Pigment	2	Included with Surface Granules
		Not included with Surface Granules
Phase I: Testing of Aggregate and Asphalt Binder	N/A	Particle Size Distribution
		Specific Gravity
		Absorption
		Void Content
		Soundness
		Rotational Viscosity
Phase II: Testing of Shingle Performance	N/A	Reflectance and Emittance
		Tear Strength

Conventional and recycled-glass modified fiberglass reinforced asphalt roofing shingles were prepared in the laboratory by varying the amount of glass cullet and conventional materials used in asphalt roof shingles, and acceptability was based upon the standard specifications described in ASTM D3462. Table 4 provides a summary of the testing methods used in this study.

Table 4 Summary of ASTM Test Methods Specifications

Property	Test Methods	Program Phase
Particle Size Distribution	ASTM C136, ASTM D422	I
Specific Gravity and Absorption	ASTM C128	I
Void Content	ASTM C1252	I
Soundness	ASTM C88	I
Rotational Viscosity	ASTM D4402	II
Reflectance & Emittance	ASTM E903, ASTM E408	II
Tear Strength	ASTM D1922	II

3.3.1 Materials Description and Processing

Three sources of recycled glass cullet were collected from C&D processing plants. Each source was presorted by color and included one source of green glass and two sources of clear glass. Approximately 85% of the glass fragments received was larger than the maximum size aggregate (2.36mm) used in producing asphalt roof shingles and needed to be processed into a smaller size. With the use of a high performance mixer, the fragments were reduced, sieved, and fractionated into sizes used in the production of conventional shingle particle sizes, see Table 2. The glass particles were then utilized in lieu of conventional mineral aggregates as top surface granules, filler material, and backdust particles.

Conventional shingle aggregates were collected and included ceramic coated roofing granules for the top surface, high calcium limestone filler material, and crushed limestone (stone dust) as the backdust. The #11 grade top surface igneous roofing granules were coated with a black ceramic pigment and were comprised of pulaskite, which is variation of syenite with little or no quartz. The limestone filler material was a ground Calcium Carbonate product (96.65% CaCO_3) with 98% passing the U.S. Standard Sieve Mesh #50 (0.300mm) and 70% passing the #200 mesh (0.075mm). For the backdust, crushed limestone #10 was obtained, reduced, and then sieved to the required size and amount. Materials used to produce both conventional and glass modified shingles included air blown asphalt binder and fiberglass matting. The binder consisted of oxidized air-blown asphalt that is suitable for use as shingle coating. The fiberglass mat consisted of a non-woven web of glass fibers and served as the substrate for the shingle.

A white pigment powder was used in the fabrication of the asphalt shingles. To this end, the powder was mixed, saturated, and oven-dried with the glass surface granules prior to placement on the surface of the asphaltic coating. The powder consisted of 98% pure titanium

dioxide (TiO_2) and was added at 8% by weight of the top surface granules. The anatase-based ultra-fine powder had a specific gravity of 3.9. The cool roof attributes of the modified shingle samples were evaluated with and without the addition of pigment powder.

3.3.2 Asphalt Shingle Preparation

In order to prepare fiberglass reinforced asphalt shingles in the laboratory, the process was divided into three steps: preparation of the formwork, preparation of the asphalt blends, and aggregate preparation. The preparation of the formwork included the thorough cleaning of an ample working surface for the placement of a fiberglass mat substrate and then securing metal forms to ensure uniform dimension of the prepared samples. The sample dimensions were 3" x 3" x 1/8" for solar reflectance testing and 3" x 2.5" x 1/8" for tear strength testing. Figure 17 shows the substrate fiberglass material and the placement of the metal forms.



Figure 17 Fiberglass mats placed in formwork

Prior to pouring the asphalt binder in the prepared forms, all aggregates were weighted and fractionated to produce the samples described in Table 5. For the specimens that did not include pigments, the following weights were used per sample: 25 grams of top surface granules,

5 grams of backdust, and 23.4 grams of filler materials. The second embodiment consisted of the addition of the white (titanium dioxide) pigment powder to the surface granules. To include pigment powder, two grams of powder were mixed with 23 grams of surface granules, saturated with water, and then oven-dried. The filler material was then uniformly mixed with 12.6 grams of liquefied asphalt binder for each sample, which was heated to 204°C. After mixing the filler material, 36 grams of asphaltic mixture was reheated to become liquefied at 230°C. The asphaltic mixture was then poured in the formwork of each shingle and then placed into the oven at 204°C for impregnation of the fiberglass. After one hour, the samples were removed from the oven and firm pressure was applied on the top surface granules in order to achieve 100% surface coverage. Upon cooling of the shingles, the forms were removed and the shingles were separated from the working surface by applying heat using a forced air heat gun. Finally, the backdust particles were applied to the back surface while keeping the underside heated.

Table 5 Description of the Shingle Specimens

Sample ID	Top Surface Material	Filler Material
X1	Control 1: Ceramic Coated Granules	Limestone
X2	Control 2: Ceramic Coated Granules	Clear Glass 1
A	Green Glass	Limestone
B	Clear Glass 1	Limestone
C	Green Glass	Green Glass
D	Clear Glass 1	Clear Glass 1
C1	Green Glass & Pigments	Green Glass
D1	Clear Glass 1 & Pigments	Clear Glass 1
G1	Clear Glass 2 & Pigments	Clear Glass 2

3.3.3 Reflectance and Emittance Testing

The main purpose of using recycling of broken and waste glass cullet in the manufacturing of asphalt roofing shingle is to alleviate heating and cooling loads in buildings by reducing solar heat flux on the roof and heat island effects by increasing the reflectivity of the roof. To assess this ability, samples were exposed to a controlled light source from a spectrophotometer in order to measure solar reflective properties in accordance with the Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres (ASTM E903). Solar absorptance and reflectance were measured by using a spectrophotometer with an absolute integrating sphere, 15°/h (Model: LPSR 200IR, AZ Technology) as shown in Figure 18. Measurements of emittance were produced by a spectrafire, shown in Figure 19, with an absolute ellipsoidal cavity, 15°/h (Model: TESA 2000, AZ Technology).

Prepared samples for reflectance testing are presented in Table 5; sample dimensions were 3" x 3" x 1/8". To consider variability in reflectance and emittance measurements, two to six readings of three replicates were conducted.

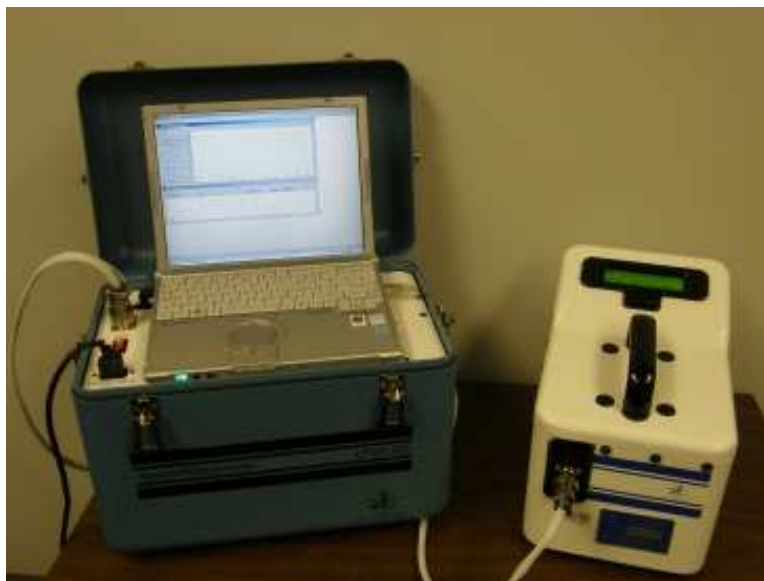


Figure 18 Spectrophotometer Instrument for Reflectance Measurements



Figure 19 Spectrafire Instrument for Emittance Measurements

Calculations of Solar Reflectance Index (SRI) under standard solar and ambient conditions are based on Approach II of the Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces (ASTM E1980). Based upon measurements of solar absorptance (α) and thermal emissivity (ϵ) of the shingle samples, the SRI was calculated for three convective coefficients (h_c) that correspond to low, medium, and high wind conditions at 5, 12, 30 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, respectively:

$$SRI = 123.97 - 141.35\chi + 9.655\chi^2$$

$$\chi = \frac{(\alpha - 0.029\epsilon)(8.797 + h_c)}{(9.5205\epsilon + h_c)}$$

3.3.4 Tear Strength Testing

To assess roof shingle tear strength, prepared asphalt shingles were tested using a pendulum tear strength tester according to the Standard Test Method for Propagation Tear Resistance of Plastic Film and Thin Sheeting by Pendulum Method (ASTM D1922). Tear strength was conducted using an Elmendorf-type tearing tester (Model: Mechanical Elmendorf Tear, Thwing-Albert). Glass-modified shingles were compared to industry minimum strength performance standards as

Table 6 illustrates the particle size characteristics of the three sources of glass cullet. Based on these characteristics, collected glass cullet sources appear to be well-graded. However, glass cullet sources are too coarse to be directly used in glass-modified asphalt shingles without processing.

Table 6 Characteristics of Recycled Glass Cullet Sources

Characteristics	Green Glass	Clear Glass 1	Clear Glass 2
Coefficient of Uniformity (C_u)	4.01	4.52	4.21
Coefficient of Curvature (C_c)	1.43	1.07	1.41
Fineness Modulus (FM)	5.63	5.34	5.63

The glass cullet particle sizes were reduced with the use of a commercial grade blender with 4" blades and were then fractionated into sizes suitable for use in roof shingles as top surface granules (2.36mm – 595 μ m), backdust particles (595 μ m – 75 μ m), and filler material (150 μ m – 45 μ m).

The cumulative particle size distribution curves of the ground glass cullet are shown in Figures 21, 22, and 23, as compared to the particle sizes of conventional aggregate used as top surface granules, backdust particles, and filler material. Results show that the laboratory grinding process effectively reduced the size particles of the recycled glass cullet and the nominal maximum aggregate size of the glass cullet, rendering it the same as conventional ceramic coated top surface granules at 2.36 mm with 7.4 to 7.7% fines. The fineness modulus was calculated for each aggregate type, and glass sources and ranged from 2.59 to 2.78 whereas the markedly smaller conventional aggregate fineness modulus was 1.93.

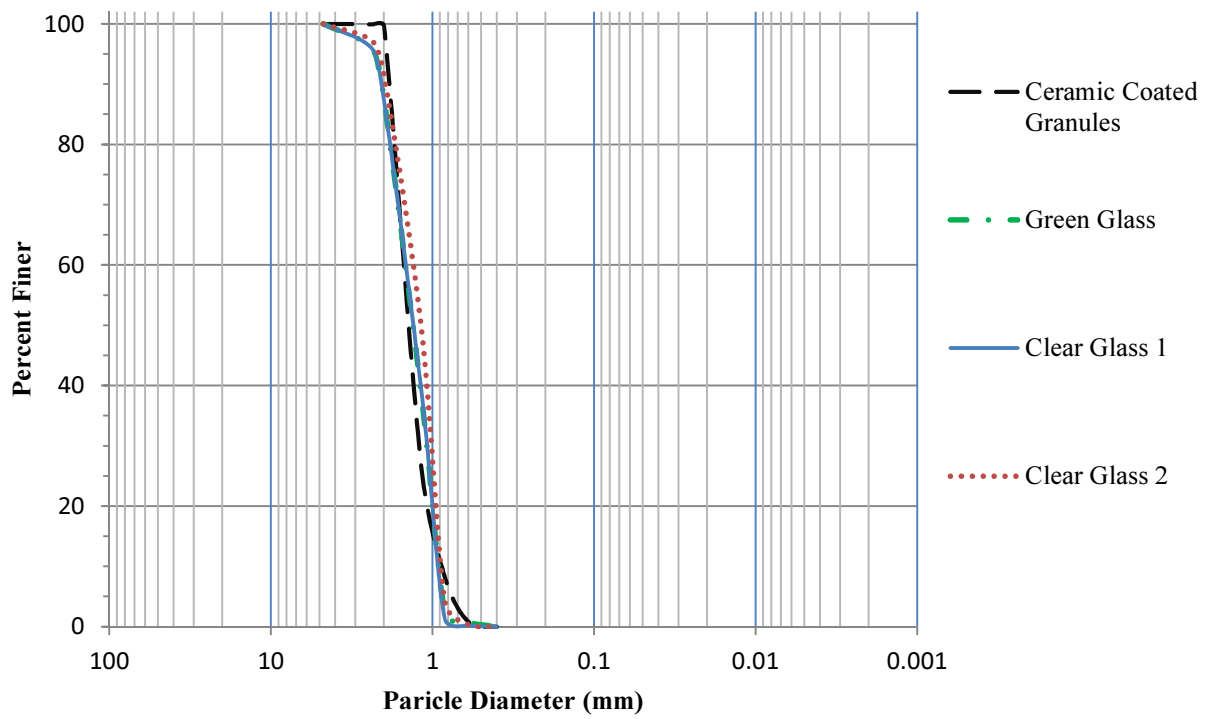


Figure 21 Cumulative Particle Size Distribution Curve of Top Surface Granules

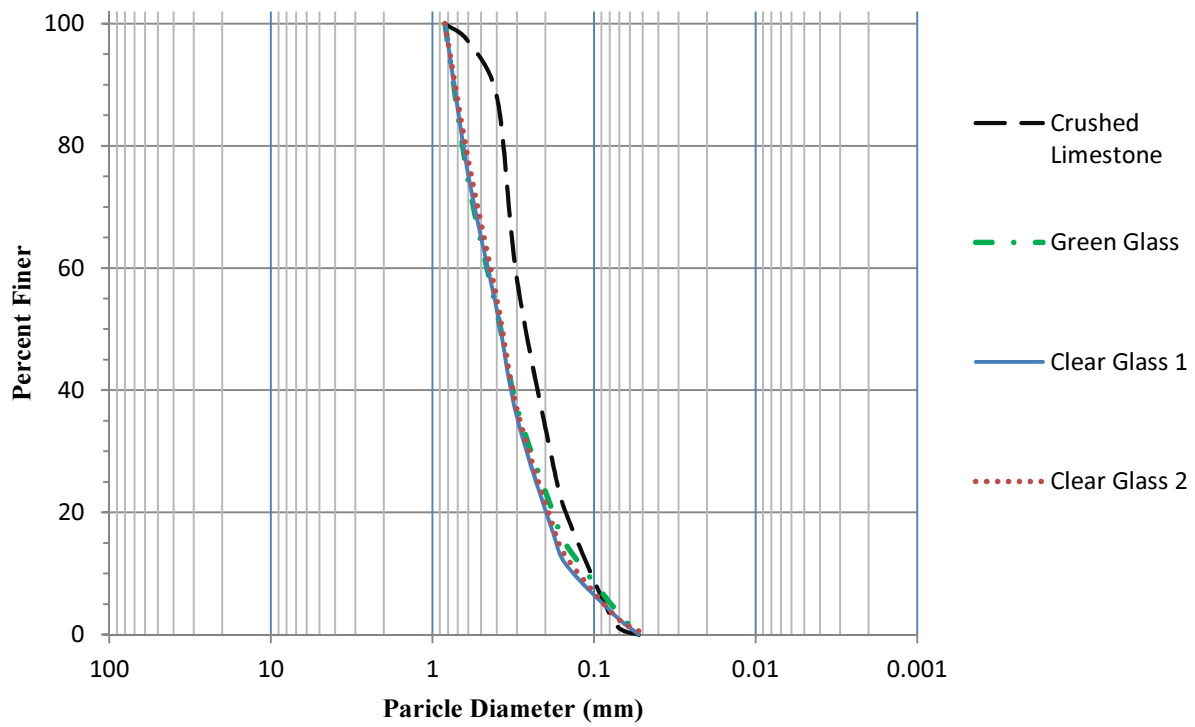


Figure 22 Cumulative Particle Size Distribution Curve of Backdust Particles

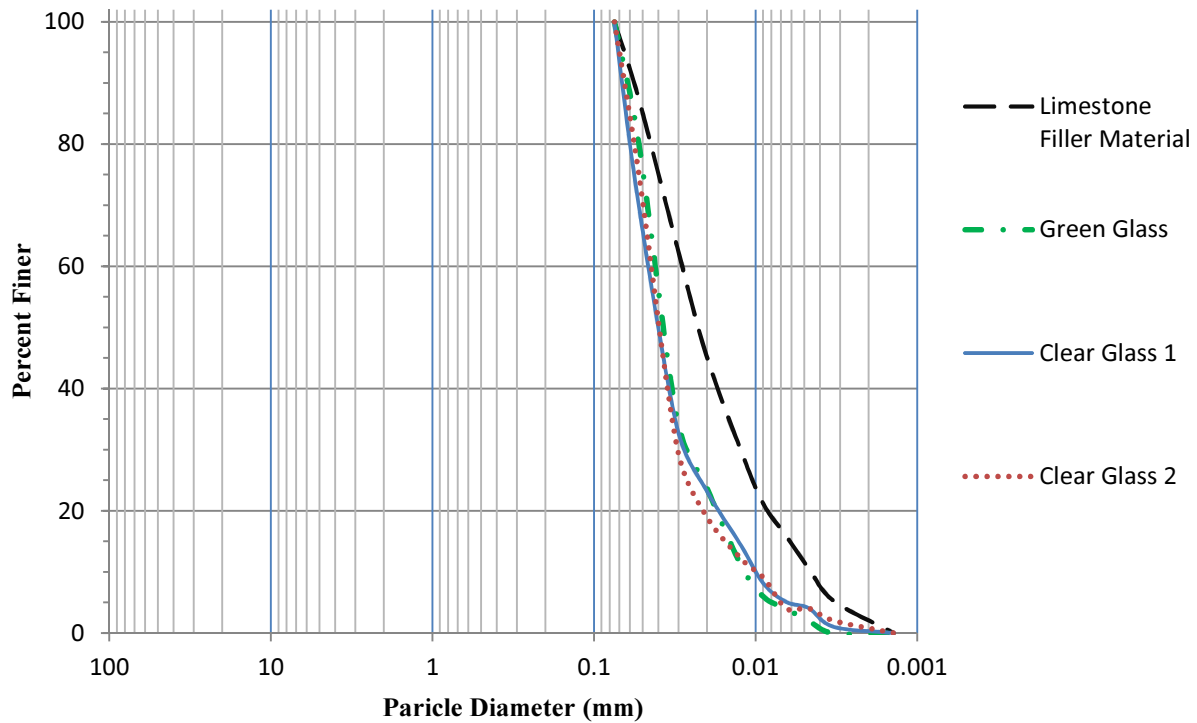


Figure 23 Cumulative Particle Size Distribution Curve of Filler Material

3.4.2 Specific Gravity, Absorption, and Soundness

A comparison of the mean specific gravity and absorption results for glass cullet and conventional shingle aggregates are shown in Table 7. Mean specific gravity results were analyzed with a one-way analysis of variance (ANOVA). The results were significant for all specific gravity conditions at a level of significance of 0.001. A Tukey post hoc test for each condition yielded individual groups for each conventional material source and grouped all three glass sources together. In general, measurements of specific gravity for recycled glass cullet were less than that of the conventional materials, and there was no significant difference between the means of the three glass sources.

Results also indicated that the absorption of recycled glass cullet samples were significantly less than the ceramic coated surface granules and the crushed limestone backdust. A Tukey post hoc test produced a Minimum Significant Difference value of 0.3015, which

revealed that there was no significant difference between the mean absorption values for all sources of glass cullet and the high calcium limestone filler. With respect to aggregate soundness, the three sources of glass cullet performed significantly better than the crushed limestone backdust.

Table 7 Comparison of Specific Gravity, Absorption, and Soundness

Type of Aggregate	Specific Gravity (OD)	Specific Gravity (SSD)	Specific Gravity (Apparent)	Absorption (%)	Soundness (% Loss)
Grinded Green Glass	2.46	2.47	2.48	0.35	4.8
Grinded Clear Glass 1	2.48	2.49	2.50	0.34	6.0
Grinded Clear Glass 2	2.47	2.48	2.50	0.40	4.9
Ceramic Coated Granules	2.56	2.58	2.62	0.83	2.8
Crushed Limestone Backdust	2.60	2.64	2.72	1.65	8.8
High Calcium Limestone Filler	2.54	2.55	2.57	0.41	N/A

3.4.3 Void Content

Table 8 shows the uncompacted void content of processed glass cullet and conventional aggregates. Results of a one-way ANOVA were significant for each aggregate layer. For top surface granules, each glass source had a greater percentage of void content with a Minimum Significant Difference (MSD) value of 0.2624%. Similarly, glass particles used as a backdust had more void content compared to conventional aggregate. For the filler material, each glass source had significantly less void content than the conventional aggregates at a significant level of 0.001. With an MSD value of 0.9758, Clear Glass 1 and Clear Glass 2 were grouped together, but were significantly different from both Green Glass and the conventional aggregates.

Table 8 Uncompacted Void Content Analysis

	Green Glass	Clear Glass 1	Clear Glass 2	Conventional Aggregates
Top Surface Granules (595 μ m - 2.36mm)	46.8%	48.1%	49.9%	45.4%
Backdust Particles (75 μ m - 595 μ m)	48.5%	51.2%	52.5%	47.9%
Filler Material (45 μ m - 150 μ m)	48.7%	50.1%	50.5%	51.5%

3.4.4 Rotational Viscosity

Table 9 presents the mean rotational viscosity results, which shows the measurements of coating blends at high temperatures. The results show that the addition of filler materials to air blown asphalt increased viscosity. A t-test statistical analysis with 95% confidence level was performed to compare the viscosity of air blown asphalt to all other blends with filler, and the results were significant (P-value = 0.0001).

Table 9 Rotational Viscosity (RV) Results

Asphalt Coating Blend	Temperature (°C)	Viscosity (Pa*s)
100% Air Blown Asphalt	204	0.332
35% Asphalt / 65% Limestone	204	2.75
35% Asphalt / 65% Green Glass	204	1.10
35% Asphalt / 65% Clear Glass 1	204	4.61
35% Asphalt / 65% Clear Glass 2	204	5.67

In comparison to the limestone filler material, green glass fillers decreased viscosity, and both sources of clear glass filler material increased viscosity measurements at 204°C. To statistically compare the results, a one-way ANOVA was conducted, and the differences were significant (P-value=0.0209). The Tukey post hoc analysis produced two different groupings.

Group A included all blends with the exception of 100% Air Blown Asphalt, and Group B consisted of all blends with the exception of Clear Glass 2.

3.4.5 Reflectance, Emittance, and Solar Reflective Index (SRI)

The mean solar reflectance and thermal emittance results are summarized in Table 10. In general, reflectance results were influenced only by the top surface material employed and were unaffected by the type of filler material used. Figure 24 shows the ceramic-coated roofing granules on the top surface of the conventional shingles and compares it to the shingles prepared with top surface glass granules, with and without the addition of white pigment powder.

To measure the effectiveness of glass cullet as a top surface material, mean reflectance values were compared for samples with the same filler material. Samples A, B, C, and D include glass cullet as a top surface material, which resulted in an increased reflectance as compared to Samples X1 and X2. The utilization of glass cullet as top surface granules resulted in a mean reflectance range increase from 0.029 to 0.050. T-test statistical analyses with 95% confidence level were performed and showed significance for Samples X1 vs. A (P-value = 0.004), Samples X1 vs. B (P-value = 0.015), and Samples X2 vs. D (P-value = 0.0005).

Although the increase was statistically significant, glass granules on the top surface alone do not meet cool roof specifications. Samples C1, D1, and G1 represent the addition of a white pigment powder to enhance the reflectance performance of the glass-modified shingles. The addition of white pigment powder to the top surface granules resulted in a mean reflectance increase from 0.168 to 0.194 for the samples with glass cullet top surface granules. T-test statistical analyses with 95% confidence level were conducted and showed significance differences for Samples C vs. C1 (P-value < 0.001) and Samples D vs. D1 (P-value < 0.001). The overall mean increase in reflectance from conventional materials to top surface glass

granules with pigments was 0.218. A t-test statistical analyses with 95% confidence level was performed and showed significant differences for Samples X2 vs. D1 (P-value < 0.001).

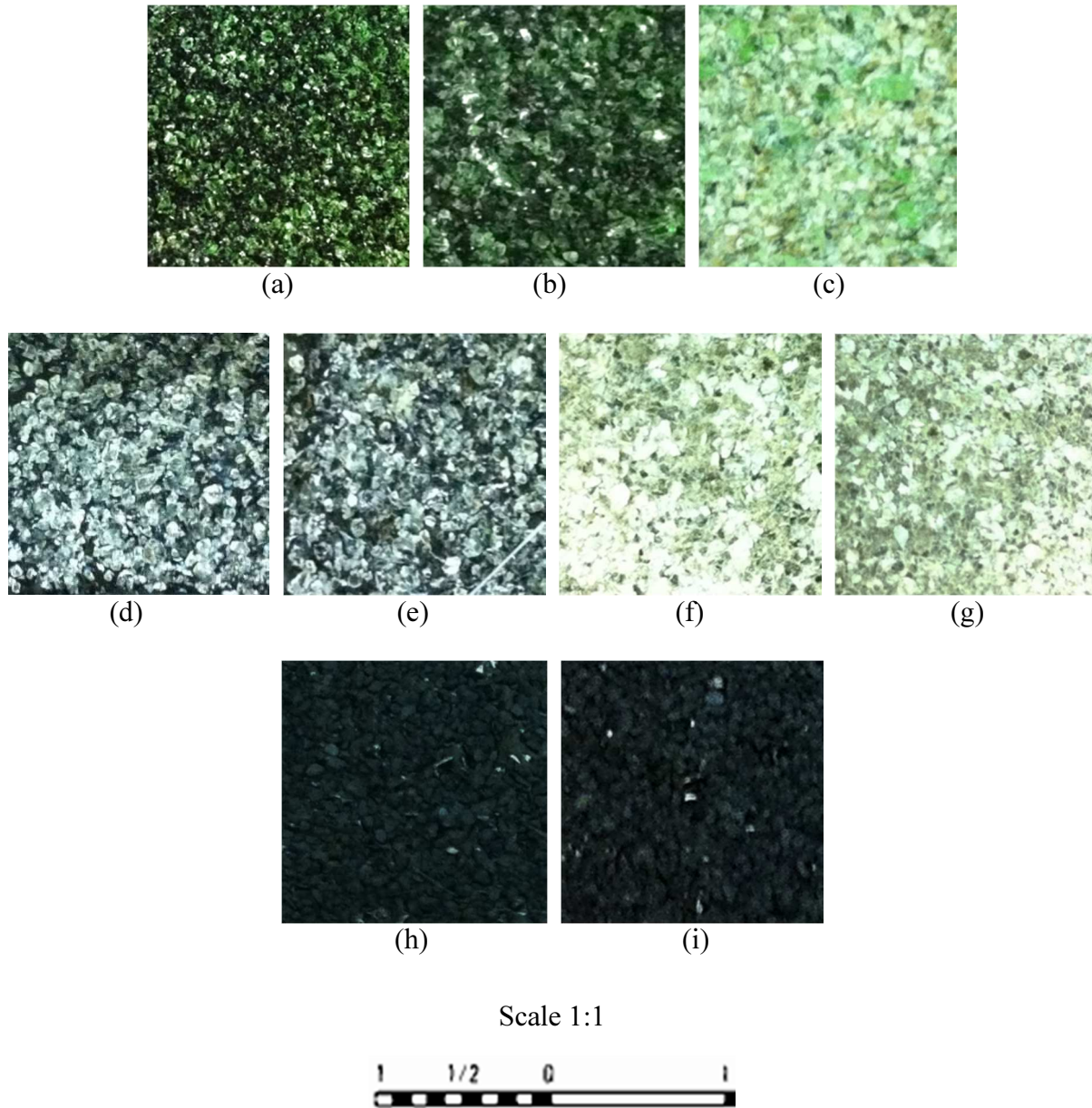


Figure 24 Qualitative Comparisons of the Top Surface of Shingle Samples Prepared: (a) Green Glass Top Surface with Limestone Filler, (b) Green Glass Top Surface with Green Glass Filler, (c) Green Glass & Pigments Top Surface with Green Glass Filler, (d) Clear Glass 1 Top Surface with Limestone Filler, (e) Clear Glass 1 Top Surface with Clear Glass 1 Filler, (f) Clear Glass 1 & Pigments Top Surface with Clear Glass 1 Filler, (g) Clear Glass 2 & Pigments Top Surface with Clear Glass 2 Filler, (h) Ceramic Coated Granules Top Surface with Limestone Filler, (i) Ceramic Coated Granules Top Surface with Clear Glass 1 Filler.

Statistical analysis also showed that the type of filler material had no significant effect on the mean reflectance values. T-test statistical analyses with 95% confidence level showed no significant differences for Samples X1 vs. X2 (P-value = 0.15), Samples A vs. C (P-value = 0.500), and Samples B vs. D (P-value = 0.865).

On the other hand, thermal emittance results were relatively unaffected by the differing top surface and filler materials. The largest mean difference between all samples was 0.027, which was the mean difference between Samples B and G1. The utilization of green glass on the top surface resulted in a mean increase of 0.011 compared to ceramic coated granules. However, the utilization of clear glass as top surface granules resulted in a mean decrease ranging from 0.006 to 0.011. T-test statistical analyses with 95% confidence level were performed and showed significant differences for Samples X1 vs. A (P-value = 0.011), but insignificant differences for Samples X1 vs. B (P-value = 0.086), and Samples X2 vs. D (P-value = 0.3606).

The addition of white pigment powder mixed with the top surface granules had no significant effect on the emittance. T-test statistical analyses with 95% confidence level were performed and showed no significant differences between Samples C vs. C1 (P-value = 0.7069), Samples D vs. D1 (P-value = 0.0622), and Samples X2 vs. D1 (P-value = 0.3637). The use of glass as a filler material versus high calcium limestone filler had mixed effects on the emittance results. T-test statistical analyses with 95% confidence level were performed and showed significance for Samples A vs. C (P-value = 0.024), but insignificant differences between Samples X1 vs. X2 (P-value = 0.9224) and Samples B vs. D (P-value = 0.4810).

Calculations of Solar Reflectance Index (SRI) at convection coefficients corresponding to low, medium, and high wind conditions are presented in Figure 25 and Table 10. Calculations are based on approach II listed in ASTM E1980 using the reflectance and emittance results

presented in Table 10. As shown in these results, the three samples with pigments (C1, D1, and G1) resulted in SRI values over the cool roof materials threshold; and therefore, can be used to construct a cool roof.

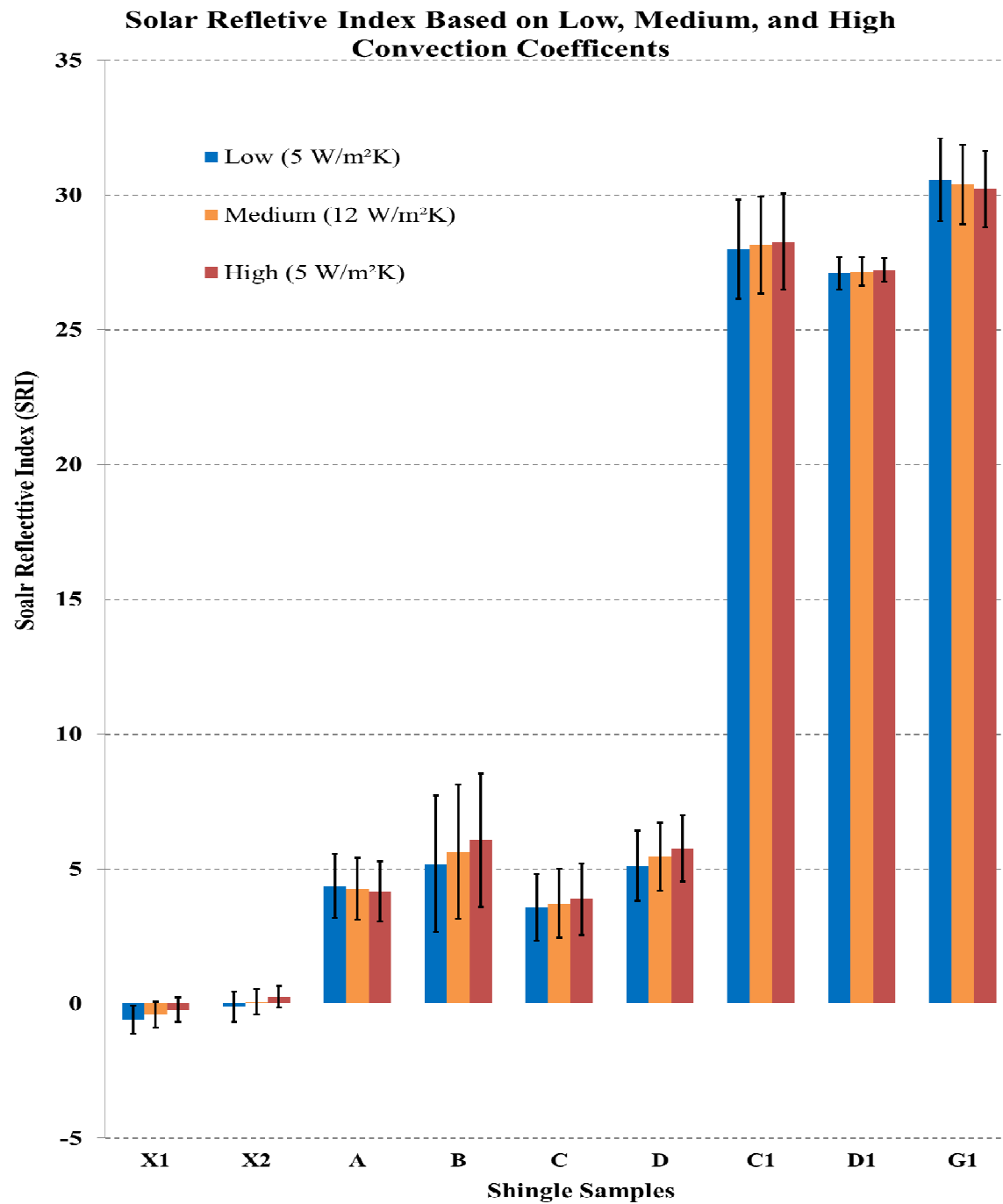


Figure 25 Solar Reflectance Index (SRI) Measurements

Table 10 Results of Reflectance, Emittance, and Solar Reflective Index (SRI)

ID	Material Composition		Solar Reflectance	Thermal Emittance at 300K	Convection Coefficient		
	Top Surface	Filler			Low	Med	High
					5 W/m²K	12 W/m²K	30 W/m²K
X1	Control 1: Ceramic Coated Granules	Limestone	0.040	0.917	-0.1	0.1	0.2
X2	Control 2: Ceramic Coated Granules	Clear Glass 1	0.036	0.917	-0.6	-0.4	-0.2
A	Green Glass	Limestone	0.069	0.928	4.4	4.3	4.2
B	Clear Glass 1	Limestone	0.090	0.906	5.2	5.6	6.1
C	Green Glass	Green Glass	0.069	0.918	3.6	3.7	3.9
D	Clear Glass 1	Clear Glass 1	0.086	0.911	5.1	5.5	5.8
C1	Green Glass & Pigments	Green Glass	0.263	0.917	28.0	28.1	28.3
D1	Clear Glass 1 & Pigments	Clear Glass 1	0.254	0.921	27.1	27.2	27.2
G1	Clear Glass 2 & Pigments	Clear Glass 2	0.275	0.933	30.6	30.4	30.2

3.4.6 Tear Strength

Initial testing involved two sets of Samples (C1 and D1) so that ten measurements could be obtained in both the longitudinal and transverse directions. However, the results of initial tear strength testing were inconclusive as no readings could be obtained within the equipment ranges. In spite of using the heaviest pendulum (6400gf) available for the Elmendorf device, the pendulum was unable to swing freely to tear the specimen, as the mass of the pendulum was supported by the sample. As shown in Figure 26, the tear began slowly, and then the shingle cracked at the jaw face and perpendicular to the tearing direction.



Figure 26 Tearing Behavior of Glass Modified Laboratory Produced Asphalt Shingles

In order to collect tear strength readings, the experiment was repeated by modifying the procedure to produce thin laboratory shingles as shown in Figure 27. The amount of coating was decreased from 36 to 26 grams, which was the thinnest specimen achievable using the procedures outlined in the experimental plan. However, as shown in Table 11, similar behaviors were exhibited when testing the thin specimens.

Table 11 Results of Elmendorf Tear Strength Testing of Thin Samples

	Sample C1				Sample D1			
Specimen	Tearing Force (gf) Machine Direction	Tearing Behavior	Tearing Force (gf) Transverse Cut	Tearing Behavior	Tearing Force (gf) Machine Direction	Tearing Behavior	Tearing Force (gf) Transverse Cut	Tearing Behavior
1	5250	Tore straight	6370	Tore straight	3780	Tore across	6270	Tore across
2	5470	Tore across	>6400	Did not tear	5630	Tore across	5120	Tore across on top; Tore straight on bottom
3	>6400	Did not tear	>6400	Did not tear	5220	Tore across	>6400	Did not tear
4	>6400	Did not tear	5380	Tore across	5150	Tore across on top; Tore straight on bottom	>6400	Did not tear
5	5060	Tore straight	>6400	Did not tear	>6400	Did not tear	6050	Tore straight
6	5150	Tore straight	>6400	Did not tear	4380	Tore across	5090	Tore straight
7	>6400	Did not tear	>6400	Did not tear	5730	Tore across on top; Tore straight on bottom	>6400	Did not tear
8	5310	Tore across on top; Tore straight on bottom	4740	Tore straight	3460	Tore across	5950	Tore across
9	>6400	Did not tear	>6400	Did not tear	3940	Tore straight	>6400	Did not tear
10	4480	Tore across on top; Tore straight on bottom	>6400	Did not tear	>6400	Did not tear	>6400	Did not tear
Average	5120		5497		4661		5696	

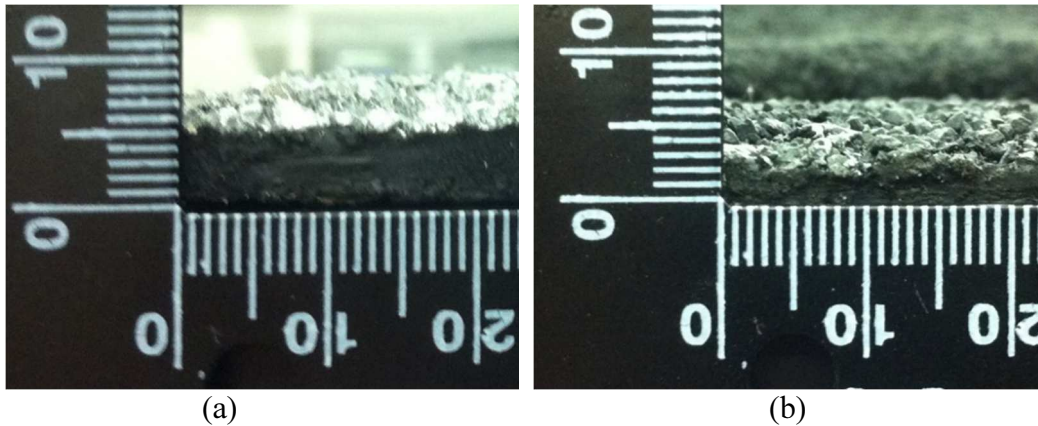


Figure 27 Comparison of Shingle Thickness: (a) Initial specimen using 36 grams of asphalt coating, (b) Thin specimen using 26 grams of asphalt coating.

It is recommended that further laboratory testing of the tear strength of shingles incorporating glass cullet be performed. To determine conclusive tear resistance values of glass-modified shingles, it is recommended to develop assembly methods that decrease the thickness of the coating layer of laboratory samples and to pursue the use of industrial manufacturing processes in order to evaluate the effects of glass fillers on actual production samples.

3.4.7 Economic Evaluation of Glass Modified Asphalt Shingles

The supply and competitive sale of cullet are based upon regional fluctuations that are affected by municipal recycling and sorting programs, collection and waste diversion methods, municipal incentive based options, costs of processing, and transportation costs (U.S. Environmental Protection Agency 2013). To take advantage of the economics in major metropolitan areas where glass collection is high, municipalities achieve savings because the cost of collecting and processing waste glass is lower than disposal costs (Gadja and VanGeem 2001). Nationwide landfilling costs range from \$20-100 per ton of waste, and in places where landfilling prices are high, waste glass is abundantly available and may be economical (Woolverton 1996).

The supply of cullet will increase as glass recovery efforts become more efficient in color sorting, crushing to size specifications, and the removal of debris. Recent technological

advances include glass beneficiation plants that use optical and x-ray technologies that take mixed cullet with contaminants, then remove the contaminants, crush, wash, and sort the glass into flint, green, and amber glass (Bohlig and Duffy 2007).

The container industry is the primary end user of recycled glass and requires cleaned, crushed, and color sorted cullet to produce new glass containers at a lower rate than extracting virgin resources. In 1992, container companies purchased cullet at approximately \$50 per ton, which set the competitive market for other industries seeking to use cullet (U.S. Environmental Protection Agency 2013). In 1996, container glass cullet was \$60 per ton for furnace ready cullet (Nash, et al. 1996). Strategic Materials, Inc. (SMI) is the largest recycler in the United States with over 40 locations, and SMI's Glass Division stated that cullet is sold to fiberglass and glass manufactures at \$80-100 per ton. A separate quote was obtained from Dlubak Glass Oklahoma who specializes in the resale of plate glass cullet for \$78-88 per ton.

Because of less stringent debris specifications, the construction industry is able to utilize mixed cullet and container cullet residuals. In order to process waste glass to meet the specifications of construction applications, the waste glass must be collected, cleaned, crushed, and screened to remove metals, plastics, paper, organics, and deleterious matter. Reddy (1999) performed a material cost comparison of glass cullet to sand as a backfill material and showed that cullet as a construction aggregate achieves an average cost savings of 50%, depending upon location, availability of conventional and recycled materials, and quality specifications.

Another common application of mixed glass cullet is glasphalt, and the economics of glasphalt are dependent upon the price of glass, hauling, crushing, and cleaning, as compared to conventional aggregate prices. However, the quantities of glass aggregate required for asphalt producers, besides New York City where asphalt plants are municipally owned, to continually

incorporate the material into their product are often prohibitive (Meyer, Egosi and Andela 2001, U.S. Department of Transportation 2012). Glasphalt has been successfully installed in New York, New Jersey, Maryland, Virginia, Connecticut, Minnesota, Iowa, Washington, and others, and while savings of \$1 per ton has been achieved, installing glasphalt has also resulted in cost increases of \$5-15 per ton (Watson 1988, Ahmed 1991, U.S. Environmental Protection Agency 1992, Schroeder 1994, Gadjia and VanGeem 2001).

In certain regions, economic incentives for cullet suppliers and construction contractors are necessary for the viability of glass cullet in construction applications to offset transportation costs and compete with conventional aggregate prices (Clean Washington Center 1996). Despite the higher costs of construction where the market for trucking in glass is not economical in parts of Minnesota, aggregate amendments in road construction bid specifications make it mandatory to use a 10% blend of recycled glass by weight in order to avoid costs in color sorting stockpiled mixed-broken glass (Minnesota Pollution Control Agency 2011).

With the right local conditions, mixed glass cullet as a construction aggregate can be competitive with conventional aggregates (Nash, et al. 1996). The price of cullet is lower than hauled-in stone aggregate in Adams County, Wisconsin as aggregate pricing varies from location to location, and is a function of raw sourcing and the distance required for transport (Resource Recycling 2005). In 1996, a recycling plant in Houston quoted unsorted glass cullet at \$10-20 per ton and mixed glass cullet free of debris at \$30-40 per ton (Woolverton 1996). In 2001, Meyer, Egosi, and Andela (2001) stated that mixed glass cullet is sold in the United States for \$1-2 per ton with effective marketing efforts versus \$5-7 per ton for conventional aggregate. However, the total shipping costs and impacts to operational changes associated with implementing multiple aggregate sources must be considered (Clean Washington Center 1996).

To perform a cost analysis of glass modified asphalt roofing shingles compared to conventional shingles, material costs for conventional aggregates and glass cullet as top surface granules and as filler material were estimated. Ceramic coated black roofing granules were quoted at \$145-185 per ton and approximately \$100 per ton for the uncoated headlap granules by Specialty Granules Inc. (SGI) and 3M Industrial Mineral Division. Because shipping and freight costs are so varied, the prices were given as free on board (FOB) at the granule manufacturing plant, where the buyer pays for all transportation costs. High calcium limestone filler material was quoted between \$17-40 per ton by Lhoist North America and Great Lakes Calcium.

The estimated price for recycled glass was provided by Strategic Materials Inc. and Dlubak Glass, and roofing granules were approximately \$131-135 per ton and \$150 per ton for filler material. However, if very large volumes became the market demand, the price for glass roofing aggregates could eventually compete with container cullet pricing and 5/8" minus plate glass recycling at \$78-100 per ton. The cost of obtaining white pigment powder at a rate of 8% by weight of the surface granules was \$3.00 per pound.

Although cool asphalt shingles currently sell for up to \$0.50 per ft² more than conventional asphalt shingles (U.S. Department of Energy 2013), the cost increase associated with implementing recycled glass granules with pigments is approximately \$0.112 per ft². Conventional ceramic coated granules, which are utilized at a rate of 0.50 pounds per ft², can be replaced by glass granules without the use of pigment powder for cost reduction of \$0.008 per ft² in material cost alone. Glass filler material at a rate of 0.46 pounds per ft² can be utilized at a cost increase of \$0.03 per ft² in place of limestone filler material. However, since filler material had no effect on reflectance or emittance, it was not included in the economic analysis. According to the Department of Energy Cool Roof Calculator, the estimated savings associated

with changing reflectance to 0.30 from a black roof for residential homes in Baton Rouge, LA is \$0.061 per ft² per year, resulting in \$91.50 savings per year for a typical 1500 ft² residence (U.S. Department of Energy 2014). As shown in Table 12, with the annual savings achieved from increasing reflectance, the payback period to offset the increased cost of glass granules with pigments is estimated at 1.8 years, which is a relatively short period of time as compared to the service life of a residential roof.

Table 12 Comparison of Material Costs

		Conventional Aggregates	Recycled Glass	Recycled Glass & Pigments
a)	Cost of Top Surface Granules (\$/ft ²)	\$0.041	\$0.033	\$0.033
b)	Cost of Pigments (\$/ft ²)	-	-	\$0.120
c)	Cost of Limestone Fillers (\$/ft ²)	\$0.007	\$0.007	\$0.007
d)	Total Cost of Aggregates [d=a+b+c] (\$/ft ²)	\$0.048	\$0.040	\$0.160
e)	Difference in Cost from Baseline Conventional Materials (\$/ft ²) Conventional Aggregates (\$0.048) Glass Aggregates (\$0.040-\$0.048= -\$0.008) Glass & Pigments (\$0.160- \$0.048=\$0.112)	Baseline	-\$0.008	\$0.112
f)	Reflectance Savings based on Department of EnergyCool Roof Calculator (\$/ft ² per year)	Baseline	\$0.016	\$0.061
g)	Estimated Payback Period [g=e/f] (years)	Baseline	Materials costs are cheaper in addition to savings in reflectance	1.8 years

3.5 Conclusions

Based upon the results of this study, recycled glass is an effective alternative as a replacement to conventional aggregates used to produce asphalt roof shingles. When processed and crushed to size specifications, recycled glass can be used as top surface granules, backdust, or filler material. When compared to the engineering properties of conventional shingle aggregates, glass cullet produced a lower specific gravity and rate of absorption value. Comparisons of soundness, void content, and effects on viscosity also showed that glass can be a suitable alternative.

The objective of this study was to increase the reflectance of asphalt roof shingles by implementing glass cullet without affecting shingle performance. Based on the results of the experimental program, the following conclusions may be drawn:

- Reflectance results were a function of only the top surface granules, as the type of filler material had no significant effect on reflectance. Green glass cullet increased reflectance by 1.7-1.9 times the value of black ceramic coated granules, and clear glass cullet reflectance was 2.25-2.50 times greater than conventional aggregates.
- To achieve cool roof features, the addition of a white pigment powder mixed together with the top surface glass granules increased SRI values ranging from 27.1-30.6.

Although there is a modest increase in the cost of materials of \$0.112 per ft², glass modified asphalt shingles with pigments can result in annual savings of \$0.061 per ft², primarily due to a reduction in cooling energy demand during the summer. It is recommended that further research continues to evaluate the durability of glass modified asphalt shingles, and in particular retesting tear strength using thinner or actual production specimens.

CHAPTER 4 – SUMMARY AND CONCLUSIONS

Implementing sustainable materials into current manufacturing processes can reduce costs, conserve energy, and lower pollution, and for a material to be considered sustainable, it should be cost efficient to the consumer and must perform comparably or better than conventional materials. This study evaluated the feasibility of using glass cullet as a substitute for conventional roof shingle aggregates in an effort to increase the reflectivity without compromising performance specifications. The first phase of the experimental program compared the engineering properties of glass cullet to conventional aggregate, and the second phase resulted in the development and performance testing of glass-modified laboratory produced shingles. Based on the results of this analysis, the following conclusions may be drawn:

- Glass cullet received from source recycling plants are generally coarse grained aggregate and therefore must be ground or crushed in order to be applied into the manufacturing process of asphalt roof shingles. Suitable shingle aggregate particle sizes include 2.36mm – 595 μ m for top surface granules, 595 μ m – 75 μ m for backdust particles, and 150 μ m – 45 μ m for filler material.
- When compared to conventional shingle aggregates, glass cullet has a lower specific gravity and absorption rate thereby making it a suitable replacement. An analysis of soundness showed that glass cullet performed better than the crushed limestone backdust but less than the ceramic coated surface granules.
- The void content of glass cullet as top surface granules and backdust particles was greater than conventional materials. The filler material glass cullet had less voids than conventional aggregates.

- The effects on rotational viscosity of glass filler material compared to high calcium limestone filler material showed mixed results, whereas green glass fillers decreased viscosity and both sources of clear glass increased viscosity measurements. Viscosity results are based upon the type of asphalt, the amount and type of fillers, and temperature, and these variations may be attributable to varying level of debris within the glass source, such as paper, plastic or foil labels, metal or plastic caps; cork, paper bags, wood, food residue, grass, and soil.
- Typical asphalt shingles are characterized by low reflectance, and results show that reflectance values were influenced only by the type of top surface aggregate utilized, and the type of filler material had no effect on reflectance values. The results show that a typical black ceramic coated asphalt shingle produced reflectance values from of 0.036-0.040. Replacing the top surface granules with green glass produced reflectance values of 0.069 and clear glass from 0.086-0.090. In order to achieve cool roof attributes, the addition of a white pigment mixed together with the top surface granules increased reflectance to 0.263 for green glass and 0.254-0.275 for clear glass. Emittance results were unaffected for all shingles ranging from 0.906-0.933.
- Glass modified shingles were tested for durability by measuring resistance to tearing, and specifications state that the minimum standard for tear strength is 1700 grams. However, in order to determine accurate readings of laboratory produced shingles, further tests and evaluation of procedures must be conducted.
- Compared to a conventional black shingles, initial costs analysis shows only a modest increase in material costs of \$0.112 per ft² to produce glass modified asphalt shingles

with pigments, but annual savings of \$0.061 per ft² per year in building energy consumption can be achieved through the increased reflectance.

Based on the results of this study, it is concluded that glass cullet can be successfully blended with conventional materials to produce a sustainable asphalt shingle that has a solar reflectance of greater than 25% without compromising performance. However, glass-modified asphalt roof shingles still requires further evaluation when considering environmental, design, and operational factors. Further research is recommended in the following areas: tear strength, cullet surface roughness effects on reflectance, granule adhesion, abrasion of cullet, shingle weathering, effects of filler amount, size, and physical characteristics on coating viscosity, penetration of asphalt, pliability, and fastener pull-through resistance. Additionally, further research is necessary to determine detailed life-cycle assessments and life-cycle cost analysis to fully understand the environmental benefits and economic feasibility of glass-modified roofing shingles.

REFERENCES

- Ahmed, Imtiaz. 1991. *Use of Waste Materials in Highway Construction*. FHWA/IN/JHRP-91/03, West Lafayette, Indiana: Joint Highway Research Project, Indiana Department of Transportation and Purdue University.
- Akbari, Hashem, Sarah Bretz, Dan M. Kurn, and James Hanford. 1997. "Peak power and cooling energy savings of high-albedo roofs." *Elsevier, Energy and Buildings* 25 117-126.
- Akbari, Hashem, S. Konopacki, and M. Pomerantz. 1999. "Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States." *Pergamon, Energy* 24 391-407.
- Akbari, Hashem, Dan M. Kurn, Sarah E. Bretz, and James W. Hanford. 1997. "Peak power and cooling energy savings of shade trees." *Elsevier, Energy and Buildings* 25 139-148.
- Akbari, Hashem, L. Shea Rose, and Haider Taha. 1999. *Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California*. Lawrence Berkeley National Laboratory.
- APB Pole Barns. 2010. *Roof Pitch*. <http://www.pole-barn.info/roof-pitch.html>.
- Arabani, M. 2011. "Effect of glass cullet on the improvement of the dynamic behaviour of asphalt concrete." *Elsevier, Construction and Building Materials* 25 1181–1185.
- Berdahl, Paul, Hashem Akbari, Ronnen Levinson, Jeffry Jacobs, Frank Klink, and Rebecca Everman. 2012. "Three-year weathering tests on asphalt shingles: Solar reflectance." *Elsevier, Solar Energy Materials & Solar Cells* 99 277–281.
- Berdahl, Paul, and Sarah E. Bretz. 1997. "Preliminary survey of the solar reflectance of cool roofing materials." *Elsevier, Energy and Buildings* 25 149-158.
- Bohlig, James W., and Sean P. Duffy. 2007. System and Methods for Recycling Glass at a Beneficiator. United States of America Patent 0012599. Jan 18.
- Bondoc, Alfredo A., Duane A. Davis, Stanley P. Frankoski, and Bruno E. Magnus. 1988. Asphalt Shingle. United States of America Patent 4717614. January 5.
- Bretz, Sarah, Hashem Akbari, and Arthur Rosenfeld. 1997. "Practical Issues for using Solar-Reflective Materials to Mitigate Urban Heat Islands." *Elsevier, Atmospheric Environment* 32 95-101.
- CertainTeed Corporation. 2013. *Steep Slope Roofing*. September 14. <http://www.certainteed.com/>.
- Clean Washington Center. 1996. "Preparation and Placement of Glassphalt." *Best Practices in Glass Recycling*. November. <http://www.cwc.org>.

- Dearborn Real Estate Education. 2013. "Principles of Home Inspection: Roofing." *RECampus*. <http://www.recampus.com/>.
- Department of the Army. 1995. *FM 5-426 Carpentry*. Washington D.C.
- Dunlop, Carlos. 2003. *The Illustrated Home*. Chicago: Dearborn Real Estate Education.
- Dyer, T. D., and R. K. Dhir. 2001. "Chemical Reactions of Glass Cullet Used as Cement Component." *American Society of Civil Engineers, Journal of Materials in Civil Engineering, Volume 13, Number 6* 412-417.
- ERSystems. 2014. *Single Ply Restoration Systems*. March 15. <http://www.ersystems.com/single-ply/>.
- Falkiewicz, Michael, and Rene Maldonado. 2010. Asphalt Shingle Coating with Improved Tear Strength. United States of America Patent 7678467.
- Gadja, John W., and Martha G. VanGeem. 2001. *A Comparison of Six Environmental Impacts of Portland Cement Concrete and Asphalt Cement Concrete Pavements*. PCA R&D Serial Number 2068, Skokie, Illinois: Portland Cement Association.
- Genesis Roofing. 2013. *What Are the Various Types of Roof Coverings?* September 19. <http://www.genesisroofinginc.com>.
- Glass Packaging Institute. 2010. *Environmental Overview Complete Life Cycle Assessment of North American Container Glass*. www.gpi.org/learn-about-glass/life-cycle-assessment.
- . 2013. October 23. <http://www.gpi.org/recycling/glass-recycling-facts>.
- Hiscocks, Peter D. 2011. "Measuring Reflectance." Syscomp Electronic Design Limited, September 16.
- Huang, Baoshan, Xiang Shu, and Guoqiang Li. 2005. "Laboratory investigation of portland cement concrete containing recycled asphalt pavements." *Elsevier, Cement and Concrete Research* 35 2008–2013.
- IKO. 2012. "The IKO Guide to Asphalt Shingles." May. www.iko.com.
- Karamberi, A, K. Orkopoulos, and A. Moutsatsou. 2007. "Synthesis of Glass-Ceramics Using Glass Cullet and Vitrified Industrial By-Products." *Elsevier, Journal of the European Ceramic Society* 27 629-636.
- Kibert, Charles J. 2008. *Sustainable Construction: Green Building Design and Delivery*. Hoboken: John Wiley & Sons, Inc.
- Konopacki, Steven J., and Hashem Akbari. 2001. "Measured energy savings and demand reduction from a reflective roof membrane on a large retail." *Lawrence Berkeley National Laboratory* 1-26.

- Kou, S. C., and C. S. Poon. 2009. "Properties of self-compacting concrete prepared with recycled glass aggregate." *Elsevier, Cement & Concrete Composites* 31 107–113.
- Kültür, Sinem, and Nil Türkeri. 2012. "Assessment of long term solar reflectance performance of roof coverings measured in laboratory and in field." *Elsevier, Building and Environment* 48 164-172.
- Kurn, Dan M., Sarah E. Bretz, Benson Huang, and Hashem Akbari. 1994. *The Potential for Reducing Urban Air Temperatures and Energy Consumption through Vegetative Cooling*. American Council for an Energy Efficient Economy Study on Energy Efficiency in Buildings.
- Leavell, Daniel N. 2003. Glass Backdust for Roof Covering. United States of America Patent 6,524,682. February 25.
- Leavell, Daniel N. 2006. "Roofing Materials." In *Industrial Rocks and Minerals, 7th Edition*, 1173-1178. Society for Mining, Metallurgy and Exploration.
- Levinson, Ronnen, and Hashem Akbari. 2002. "Effects of composition and exposure on the solar reflectance of portland cement concrete." *Pergamon, Cement and Concrete Research* 32 1679-1698.
- Levinson, Ronnen, Hashem Akbari, and Paul Berdahl. 2010. "A novel technique for the production of cool colored concrete tile and asphalt." *Elsevier, Solar Energy Materials & Solar Cells* 94 946–954.
- Levinson, Ronnen, Hashem Akbari, Steve Konopacki, and Sarah Bretz. 2005. "Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements." *Elsevier, Energy Policy* 33 151–170.
- Levinson, Ronnen, Paul Berdahl, Hashem Akbari, William Miller, Ingo Jöedicke, Joseph Reilly, Yoshi Suzuki, and Michelle Vondran. 2007. "Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials." *Elsevier, Solar Energy Materials & Solar Cells* 91 304–314.
- MacDonald, J. M., G. E. Courville, E. I. Griggs, and T. R. Sharp. 1989. "A Guide for Estimating Potential Energy Savings from Increased Solar Reflectance of a Low-Sloped Roof." *4th Thermal Performance of the Exterior Envelopes of Buildings*. Orlando, FL: U.S. Department of Energy. 348-357.
- Made How. 2013. "Shingle." <http://www.madehow.com/>.
- Maupin, G. W. 1998. *Effect of Glass Concentration on Stripping of Glasphalt*. Charlottesville: Virginia Transportation Research Council.
- McPherson, Greg, James R. Simpson, Paula J. Peper, Scott E. Maco, and Qingfu Xiao. 2005. "Municipal Forest Benefits and Costs in Five US Cities." *Journal of Forestry* 411-416.

- Meyer, C., N. Egosi, and C. Andela. 2001. "Concrete with Waste Glass as Aggregate." *Recycling and Re-use of Glass Cullet*. International Symposium Concrete Technology Unit of American Society of Civil Engineers and University of Dundee.
- Minnesota Pollution Control Agency. 2011. *Glass as road aggregate*. March 21. <http://www.pca.state.mn.us>.
- Nash, Phillip T., Priyantha Jayawickrama, Sanjaya Senadhera, Krishnan Viswanathan, Richard Wm. Tock, and Binli Woolverton. 1996. *Use of Glass Cullet in Roadway Construction Laboratory Testing and Specification Development*. Submitted to Texas Department of Transportation, Lubbock: Texas Tech University.
- National Institute of Building Sciences. 2009. "National Institute of Building Sciences." *Building Envelope Design Guide - Introduction*. June 1. http://www.wbdg.org/design/env_introduction.php.
- National Roofing Contractors Association. 2013. *Roof system types*. August 20. <http://www.nrca.net/roofing/Roof-system-types-891>.
- Nations Roof. 2013. *Cool Roofs*. http://www.nationsroof.com/Cool_Roofs.htm.
- Pagen, Charles A, George Stepien, Jr., and Paul A. Morris. 1986. Coating Formulation for Inorganic Fiber Mat Based Bituminous Roofing Shingles. United States of America Patent 4,588,634. May 13.
- Park, Seung Bum, Bong Chun Lee, and Jeong Hwan Kim. 2004. "Studies on mechanical properties of concrete containing waste glass aggregate." *Pergamon, Cement and Concrete Research* 34 2181–2189.
- Parker, Danny S., and Stephen F. Barkaszi, Jr. 1997. "Roof solar reflectance and cooling energy use: field research results from Florida." *Elsevier, Energy and Buildings* 25 105-115.
- Polley, Craig, Steven M. Cramer, and Rodolfo V. de la Cruz. 1998. "Potential For Using Waste Glass In Portland Cement Concrete." *American Society of Civil Engineers, Journal of Materials in Civil Engineering* 210-219.
- Poole, Mark. 2011. "Composition Shingle Manufacturing Process." March 6. <http://ezinearticles.com/?Composition-Shingle-Manufacturing-Process&id=6042097>.
- Reddy, Krishna R. 1999. "Use of Glass Cullet as Backfill Material for Retaining Structures." *International Conference on Solid Waste Technology and Management, Philadelphia* 1-8.
- Reindl, John. 2003. "Reuse/Recycling of Glass Cullet for Non-Container Uses." *Dane County Department of Public Works*.

- Saadatian, Omidreza, K. Sopian, E. Salleh, C. H. Lim, Safa Riffat, Elham Saadatian, Arash Toudeshki, and M. Y. Sulaiman. 2013. "A review of energy aspects of green roofs." *Elsevier, Renewable and Sustainable Energy Reviews* 23 155–168.
- Sandler, Ken. 2003. "Analyzing What's Recyclable in C&D Debris." *Biocycle*, November: 51-54.
- Schroeder, Robin L. 1994. "The Use of Recycled Materials in Highway Construction." *Public Roads*, Autumn: Vol. 58 No.2.
- Shaw, D. E. 1999. "The Use of Fly Ash in the Manufacture of Asphalt Shingles." *Proceedings of the Fourth International Symposium on Roofing Technology* 113-118.
- Shayan, Ahmad, and Aimin Xu. 2004. "Value-added utilisation of waste glass in concrete." *Pergamon, Cement and Concrete Research* 34 81–89.
- Shi, Caijun, and Keren Zheng. 2007. "A review on the use of waste glasses in the production of cement and concrete." *Elsevier, Resources, Conservation and Recycling* 52 234–247.
- Simpson, J. R., and E. G. McPherson. 1997. "The effects of roof albedo modification on cooling loads of scale model residences in Tuscon, AZ." *Elsevier, Energy and Buildings* 25 127-137.
- Synnefa, A., M. Santamouris, and I. Livada. 2006. "A study of the thermal performance of reflective coatings for the urban environment." *Elsevier, Solar Energy* 80 968–981.
- Tan, Kiang Hwee, and Hongjian Du. 2013. "Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties." *Elsevier, Cement & Concrete Composites* 35 109–117.
- Tsuni, Alexia. 2003. "Vouhead Weather." June. <http://weather.vouhead.gr>.
- U.S. Department of Energy. 2013. "Office of Energy Efficiency & Renewable Energy." Cool roofs are ready to save energy, cool urban heat islands, and help slow global warming. December. https://www1.eere.energy.gov/buildings/pdfs/cool_roof_fact_sheet.pdf.
- . 2014. *Office of Energy Efficiency & Renewable Energy*. January 15. <http://energy.gov/>.
- . 2014. DOE Cool Roof Calculator. February 18. <http://web.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>.
- U.S. Department of Transportation. 2012. "Federal Highway Administration." *User Guidelines for Waste and Byproduct Materials in Pavement Construction*. April 23.
- U.S. Environmental Protection Agency. 1992. "Markets for Recovered Glass." *Glass*. June 17. <http://www.epa.gov/osw/conserve/materials/glass.htm>.

- . 2010. "Asphalt Shingles." October 28.
<http://www.epa.gov/climatechange/wycd/waste/downloads/asphalt-shingles10-28-10.pdf>.
- . 2013. *Common Wastes & Materias*. June 17.
<http://www.epa.gov/osw/conserva/materials/glass.htm>.
- . 2013. *Sustainable Materials Management*. November 22.
<http://epa.gov/epawaste/conserva/smm/index.htm>.
- . 2014. *State and Local Climate and Energy Program*. February 21.
<http://www.epa.gov/hiri/index.htm>.
- Vardoulakis, E., D. Karamanis, M. N. Assimakopou, and G. Mihalakakou. 2011. "Solar cooling with aluminium pillared clays." *Elsevier, Solar Energy Materials & Solar Cells* 95 2363–2370.
- Watson, J. 1988. "When the Tire Hits the Glasphalt." *Resource Recycling Magazine*.
- Whitaker, Robert H., Allen E. Smith, and David R. Puryear. 2010. Mineral Filler Composition. United States of America Patent 7,833,339. November 16.
- Woolverton, Amanda Binli. 1996. *Use of Glass Cullet in Roadway Construction*. Masters Thesis, Lubbock: Texas Tech.
- Wray, Craig, and Hashem Akbari. 2008. "The effects of roof reflectance on air temperatures surrounding a rooftop condensing unit." *Elsevier, Energy and Buildings* 35 11-28.
- Wu, S., W. Yang, and Y. Xue. 2004. "Preparation and properties of glass–asphalt concrete." *Wuham (China): Key Laboratory for Silicate Materials Science and Engineering of Ministry of Education, Wuham University of Technology*.
- Xu, Tengfang, Jayant Sathaye, Hashem Akbari, Vishal Garg, and Surekha Tetali. 2012. "Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions." *Elsevier, Building and Environment* 48 1-6.

APPENDIX

1 Economic Analysis Worksheet

		Conventional Aggregates	Recycled Glass	Recycled Glass & Pigments
a)	Cost of Top Surface Granules (\$/ton)	\$165	\$131	\$131
b)	Cost of Top Surface Granules (\$/lbs) [b=a/2000]	\$0.083	\$0.066	\$0.066
c)	Usage Rate of Top Surface Granules (lbs/ft ²) - Based on shingle antomy findings in experimental data	0.5	0.5	0.5
d)	Square Foot Cost of Top Surface Granules (\$/ft ²) [d=b*c]	\$0.041	\$0.033	\$0.033
e)	Cost of Pigments (\$/ton)	-	-	\$6,000
f)	Cost of Pigments (\$/lbs) [f=e/2000]	-	-	\$3.00
g)	Usage Rate of Pigments (lbs/ft ²) - Based on 8% by weight of top surface granules as utilized in experimental procedure	-	-	0.04
h)	Square Foot Cost of Pigments (\$/ft ²) [h=f*g]	-	-	\$0.120
i)	Cost of Limestone Filler Materials (\$/ton) - Only limestone filler was used for this analysis since glass fillers measured no effects on reflectance or emittance	\$28.50	\$28.50	\$28.50
j)	Cost of Limestone Filler Materials (\$/lbs) [j=i/2000]	\$0.014	\$0.014	\$0.014
k)	Usage Rate of Limestone Filler Materials (lbs/ft ²) - Based on shingle antomy findings in experimental data	0.469	0.469	0.469
l)	Square Foot Cost of Limestone Filler Materials (\$/ft ²) [j=k*l]	\$0.007	\$0.007	\$0.007
m)	Total Square Foot Cost of Aggregates (\$/ft ²) [m=d+h+l]	\$0.048	\$0.040	\$0.160
n)	Square Foot Cost Difference from Conventional Materials (\$/ft ²) - Based on Total Square Foot Costs of Aggregates. Conventional Roof (\$0.048); Glass Aggregates (\$0.040-\$0.048=-\$0.008); Glass & Pigments (\$0.160-\$0.048=\$0.112)	Baseline	-\$0.008	\$0.112
o)	Reflectance Savings (\$/ft ² per year) - Based on Department of Energy Cool Roof Calculator. Inputs: Baton, LA; R-value 5 (low); Emittance 92; Reflectance Glass 9; Reflectance Glass & Pigments 30; Average summer & winter costs and efficiency	Baseline	\$0.016	\$0.061
p)	Estimated Payback Period (years) - Based upon savings achieved from reflectance and materials cost differences [p=n/o]	Baseline	Materials Costs are cheaper in addition to savings in reflectance	1.8 years

2 Department of Energy Cool Roof Calculator for Glass Granules

My State

Louisiana ▼

My City

Baton Rouge ▼

Click to see [Data for All 243 Locations](#)

My Proposed Roof:

R-value (HIGH=20; AVG=10; LOW=5) [h·ft²·°F/Btu]

5

Solar reflectance, SR (HIGH=80; AVG=50; LOW=10) [%]

9

Infrared emittance, IE (HIGH=90; AVG=60; LOW=10) [%]

92

My Energy Costs and Equipment Efficiencies

Summertime cost of electricity (HIGH=0.20; AVG=0.10; LOW=0.05) [\$/KWh]

.1

Air conditioner efficiency (Coefficient of Performance) (HIGH=2.5; AVG=2.0; LOW=1.5)

2

Energy source for heating (choose one)

☒ Electricity ☐ Fuel

If electricity, wintertime cost (HIGH=0.20; AVG=0.10; LOW=0.05) [\$/KWh]

.1

If fuel, cost (Natural gas: HIGH=1.00; AVG=0.70; LOW=0.50) [\$/Therm]

(Fuel oil: 2002 East coast=0.85; 2002 Midwest=0.70) [\$/Therm]

Heating system efficiency (Furnace or boiler: HIGH=0.8; AVG=0.7; LOW=0.5)

(Electric heat pump: HIGH=2.0; AVG=1.5) (Electric resistance: 1.0)

1.5

Calculate My Annual Savings Relative to a Black Roof

Net Savings [\$/ft² per year]

0.009

Cooling savings [\$/ft² per year]

0.013

Heating savings (heating penalty if negative) [\$/ft² per year]

-0.004

<http://web.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>

3 Department of Energy Cool Roof Calculator for Glass Granules with Pigments

My State

Louisiana ▼

My City

Baton Rouge ▼

Click to see [Data for All 243 Locations](#)

My Proposed Roof:

R-value (HIGH=20; AVG=10; LOW=5) [h·ft²·°F/Btu]

5

Solar reflectance, SR (HIGH=80; AVG=50; LOW=10) [%]

30

Infrared emittance, IE (HIGH=90; AVG=60; LOW=10) [%]

92

My Energy Costs and Equipment Efficiencies

Summertime cost of electricity (HIGH=0.20; AVG=0.10; LOW=0.05) [\$/KWh]

.1

Air conditioner efficiency (Coefficient of Performance) (HIGH=2.5; AVG=2.0; LOW=1.5)

2

Energy source for heating (choose one)

☒ Electricity ☐ Fuel

If electricity, wintertime cost (HIGH=0.20; AVG=0.10; LOW=0.05) [\$/KWh]

.1

If fuel, cost (Natural gas: HIGH=1.00; AVG=0.70; LOW=0.50) [\$/Therm]

(Fuel oil: 2002 East coast=0.85; 2002 Midwest=0.70) [\$/Therm]

Heating system efficiency (Furnace or boiler: HIGH=0.8; AVG=0.7; LOW=0.5)

(Electric heat pump: HIGH=2.0; AVG=1.5) (Electric resistance: 1.0)

1.5

Calculate My Annual Savings Relative to a Black Roof

Net Savings [\$/ft² per year]

0.061

Cooling savings [\$/ft² per year]

0.075

Heating savings (heating penalty if negative) [\$/ft² per year]

-0.015

<http://web.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>

4 Summary of Shingle Development and Pilot Testing

The development and production of laboratory produced fiberglass roofing shingles with increased reflectance underwent multiple iterations. The initial step included the development of control samples, which was comprised of ceramic coated top surface granules, asphalt coating with limestone fillers, a fiberglass mat, and crushed limestone backdust particles. The next step was the incorporation of recycled glass in order to measure the effects on reflectance. Glass modified roofing shingles consisted of top surface glass granules, asphalt coating with glass fillers, a fiberglass mat, and glass backdust particles. It was noted that the filler material had no effect on Solar Reflectance Index (SRI) measurements, and glass granules on the top surface increased reflectance and had no effect on emittance values. However, despite the increased reflectance performance, the shingles were not above the cool roof threshold at 0.25 reflectance.

To increase the reflective performance of glass as a top surface granule, trial and error testing was performed. The first method included the use of white liquid water based paint mixed together with the asphalt coating. However, in order to achieve satisfactory levels of reflectance, the coating ratios had to consist of over 50% by weight of paint, and at that level, the asphalt coating's properties were altered to where mixing and handling at high temperatures was not possible. Another method considered was painting the top surface of the coating prior to the placement of top surface granules. However, this method was not achievable due to the high temperatures and fast pace of work required causing concerns with top surface granule adhesion. The next method consisted of sprinkling a white pigment powder onto the surface of the shingle prior to the placement of the glass granules, and this method also caused major concerns with granule adhesion. By mixing the white pigments together with the top surface granules and applying them at the same time, all workability and adhesion concerns were resolved.

VITA

Lieutenant Commander Kiletico is from Marrero, LA and attended Louisiana Tech University, where he received a Bachelor of Science in Civil Engineering in August 2003. He enlisted in the United States Navy Civil Engineer Corps Collegiate Program in March 2003, reported to Officer Candidate School (OCS) in Pensacola, FL in December 2003, and was commissioned in March 2004.

His first assignment upon completion of Naval Civil Engineer Corps Officers School (CECOS), was to Naval Mobile Construction Battalion Three (NMCB 3) in Port Hueneme, CA. He completed unit deployments to Guam, Iraq, and Kuwait, where he served as an Assistant Company Commander, Assistant Officer in Charge of Detail Buehring, and Battalion Embarkation & Movement Control Officer. In June 2006, he was assigned to Naval Air Station Fallon, NV as the Officer in Charge of Construction Battalion Maintenance Unit Three Zero Three (CBMU 303) Detachment Fallon, where he completed a deployment onboard the USS BOXER (LHD 4) to Guatemala, El Salvador, and Peru in support of the humanitarian and civic assistance mission Continuing Promise 2008.

In January 2009, he reported to Naval Facilities Engineering Command (NAVFAC) with the Officer in Charge of Construction Marine Corps Installations East at Camp Lejeune, NC. He was assigned to the Stone Bay Field Office as the Project Engineer for the U.S. Marine Corps Special Operations Command (MARSOC) Design-Build Complex. In July 2011, he reported to Navy Personnel Command in Millington, TN and served as the CEC LTJG/ENS Detailer and Defense Acquisition Community Training Representative. In June 2013, he reported to Louisiana State University where he is currently in pursuit of a Master of Science in

Construction Management and will be assigned as the Public Works Officer of Naval Air Station Joint Reserve Base New Orleans, LA in June 2014.

LCDR Kiletico is a designated Seabee Combat Warfare Officer. His awards include four Navy Commendation Medals, Army Commendation Medal, Navy & Marine Corps Achievement Medal, Navy “E”, Fleet Marine Force Service Ribbon, National Defense Service Medal, Iraq Campaign Medal, Global War on Terrorism Expeditionary and Service Medals. LCDR Kiletico is a registered Professional Engineer in North Carolina and a member of the Society of American Military Engineers.