The Use of Synthetic Lightweight Aggregates as a Component of Sustainable Designs

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ABSTRACT

Sustainable design principles attempt to utilize local materials in ways that reduce the impact of the proposed development so that it behaves more like a natural environment. With respect to site development, the goal is to utilize construction materials made with high recycled content as well as to recycle waste construction materials. This paper presents the incorporation of synthetic lightweight aggregates (SLA) in pilot-scale studies of the use of sustainable design on a university campus. SLA is a coarse aggregate (greater than 4 mm particle size) composed of 80% fly ash and 20% recycled thermoplastic. Specifically, SLA was used as one of the components of an extensive green roof system and was incorporated in the design of pervious, replacement steps for an exterior stairway. As a part of the green roof system, the SLA served the role as the drainable substrate for plant growth. In the pervious step design, the SLA provided a durable lightweight alternative to traditional sand and gravel. The results of the work indicate that SLA provides an alternative and appropriate, lightweight construction material that can be utilized in sustainable design concepts.

Introduction

Synthetic lightweight aggregates (SLAs) are an innovative construction material created from the co-extrusion of recycled mixed plastics and fly ash. Centered at Tufts University and the University of Massachusetts at Lowell, previous work has shown that SLAs can be utilized in geotechnical, concrete, and asphalt applications (Kashi etal., 2001; Malloy etal., 2001; Kashi etal 2003; Hooper etal., 2004; Swan and Sacks, 2005; and Elsayed and Swan, 2007). As shown in Figure 1, SLAs are manufactured by melt-blending a fly ash “filler” with plastics at the desired proportions using a co-rotating intermeshing twin-screw extruder. The resulting granulated material resembles a dark gray sand and fine gravel. Over the last decade, SLA research has focused on the physical and mechanical properties of various SLA compositions. Work has also been done in the manufacturing of SLAs including different SLA formulations and manufacturing methods, and

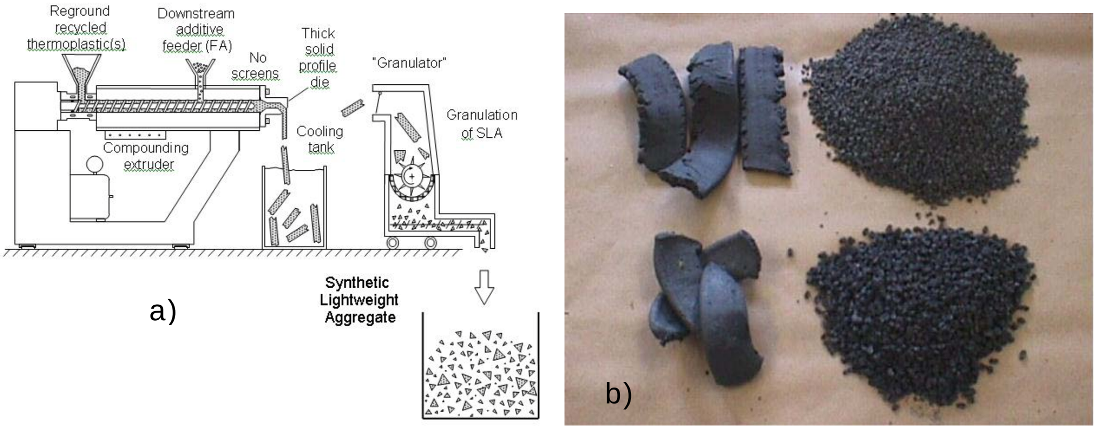


Figure 1 Schematic of Synthetic Lightweight Aggregate Manufacturing (a) and the Solid Die and Resulting Synthetic Lightweight Aggregate after Granulation (b)

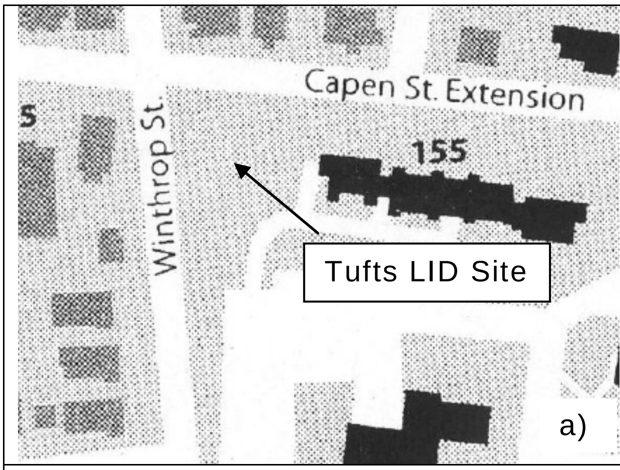
laboratory and industrial plant-scale manufacturing methods. The results of these efforts indicate a strong potential for the large-scale production and use of SLAs in engineered applications. This paper focuses on the use of SLA in applications which are commonly considered to be sustainable engineering or "green". Most notably, this work has evaluated the use of SLA as the aggregate in pervious outdoor steps and as a component of an extensive green roof system. These projects are described below.

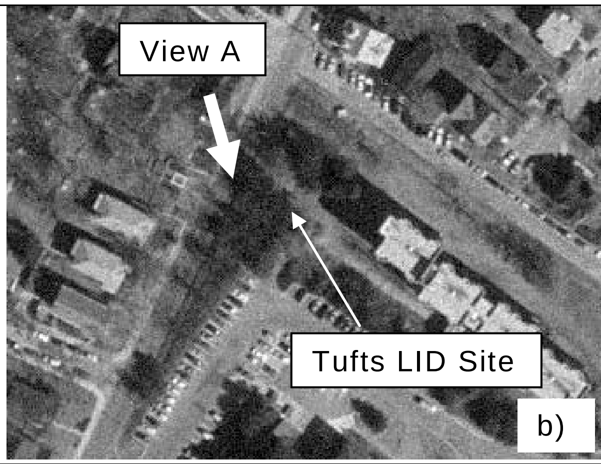
<u>SLA Used in Creating Pervious Steps</u>

Low impact development (LID) and sustainable design manipulate landscapes impacted by human development to behave more like a natural environment. LID and sustainable designs are becoming more frequently used today. The goal is for a site to have increased infiltration and decreased runoff and make it easier to maintain. Two student project teams at Tufts University illustrated to Tufts how LID can be applied on the campus. Their projects involved evaluating a site on the northwest side of Tufts University behind the Carmichael Residence Hall (Carmichael) and Wren Residence Hall (Wren) to determine potential design options to implement that would have both low impact and sustainable (see Figure 2). The site consists of a steeply sloping topography running down from the Carmichael/Wren parking lot towards Capen Street Extension (to the north) and Winthrop Street (to the west).

Scope of Project

The team came up with seven design components or "phases" that focus on different impacts on the area. These phases include: the Wren staircase, Wren groundcover, Winthrop Street slope stabilization, enhanced infiltration basin along Capen Street slope, pervious pavement for the Carmichael/Wren parking lot, drainage away from the Wren driveway, site lighting, and community education. Though all phases of the project are beneficial, breaking up the design in this way increased the likelihood of implementation





View A (Stairs going up from Capen Street)

Figure 2 – Site Location Behind Carmichael and Wren Residence Halls

as each part's feasibility can be estimated independently of the others. Each phase was designed to incorporated LID and sustainable design elements along with consideration of the needs of the client (Tufts University) by being easy to maintain and aesthetically pleasing.

The proposed phase of revitalizing the Wren staircases consisted of replacing the existing crushed gravel surface overlaying a clayey soil base with a more pervious surface and near surface layers of SLA. A review of the proposed LID Wren staircase phase is presented below. The work done was based on existing site constraints; e.g., low annual maintenance, long-term effectiveness, aesthetics, community acceptance, simplicity and speed of implementation, and total cost (initial capital).

The Wren stairs are located on the corner of Winthrop Street and Capen Street and lead up to the Carmichael parking lot (see Figure 2c). The stairs are constructed of wood framing filled with compacted clayey soil covered by crushed gravel. High maintenance of the stairs is required due to the necessity to replace gravel and ensure that the stairs are safe for pedestrians. Additionally, snow removal is problematic due to the gravel surface. The compacted, low permeable soil also does not allow for infiltration and instead causes runoff down the stairs and onto Capen Street.

Design Solution

To address the both the maintenance costs and the runoff on the Wren stairs, it was necessary to have a flat surface that will allow for easy snow removal, as well as provide increased infiltration. One proposed solution was to create a layered system of course gravel (crushed stone) overlaid by a pervious asphalt-based pavement containing synthetic lightweight aggregate (SLA).

Laboratory studies consisted of a pilot study of mock steps. The step design called for a layer of medium sized stone (up to 2 mm particle size) topped with a cohesive, yet permeable SLA layer. The composition of this layer to be used was decided trough a trial and error approach of different mixtures. In order, they included

- Mix 1: SLA adhered with outdoor carpet adhesive. The adhesive was mixed with medium sized SLA at 20% adhesive/80% SLA by weight. The sample showed much more cohesion despite only having 24 hours to dry with a gray and tan final appearance.
- Mix 2: SLA adhered with tile flooring adhesive. The adhesive was mixed with medium-sized SLA at a 20% adhesive to 80% SLA formulation, by weight. The same showed slightly less cohesion, remained sticky weeks after being set, and dried charcoal grey in color.
- Mix 3: SLA adhered with roofing tar. The roofing tar was mixed with medium sized SLA at varying adhesive-to-SLA compositions by weight from 10 to 20%. The resulting product, while permeable, had little cohesive strength.
- Mix 4: Multi-layered SLA adhered with outdoor carpet adhesive. For this composition, fine-sized (<No. 8 sieve) SLA particles were placed over the medium-sized SLA. The behavior is similar to Mix 1 (the medium-sized SLA only); however, the fine-sized SLA provides a smoother and cleaner looking final surface.

The ultimate goal, replacing the existing steps of a thin layer of crushed stone overlying a clayey soil base, required an increase in the infiltration rate of water through the step. For evaluation, crude “percolation” tests were performed on the various mixtures. For the various SLA mixtures, approximately 5-cm-thick samples of the mixtures were compacted into 7.5-cm diameter, 12-cm high, cylindrical molds. The remainder of the mold was filled with tap water and the rate at which the water level dropped was recorded as the infiltration rate. For the existing steps, a cylindrical mold was placed slightly below a step’s surface, into the clayey soil base, and filled with water. Again the rate at which the water level dropped was recorded as the infiltration rate. Table 1 presents the results of these tests.

Table 1 Percolation Test Results

Sample/Mixture	Existing Step	Mix 1	Mix 2	Mix 3	Mix 4
Infiltration Rate (cm/s)	1.92×10^{-4}	2.98×10^{-2}	2.41×10^{-2}	6.92×10^{-3}	3.19×10^{-2}

As shown in the table, the SLA mixtures had infiltration rates 10 to 100 times greater than those measured for the existing step indicating that the SLA mixtures would be considerably more permeable than the existing steps.

Benefits and Concerns

It is anticipated that maintenance costs will be reduced and permeability can be increased by replacing the current fill in the stairs with a flat, permeable surface underlain by a more pervious base material. Additionally, the SLA chosen for the wearing surface is composed of recycled plastic and coal combustion by-product (fly ash); thus, illustrating how to reuse waste materials constructively and at a low cost. Current initial cost estimates for step material replacement is approximately $3000; based on material costs and installation. Maintenance costs are estimated to be lower than what is currently expended because annual replacement of gravel will no longer be necessary.

Uncertainties remain with this proposed design. It is unknown how the mixture of the SLA and adhesives will stand up to the elements presented by the New England winter climate. Some these concerns include how the cohesion will stand up to extreme temperatures, to large amounts of rainfall, and to annual wear-and-tear by pedestrian traffic. It is recommended that the mock steps created in the pilot study be placed out in the elements and monitored as to how it holds up before continuing with the placement of the design. It is also recommended that freeze/thaw experiments be conducted. Another uncertainty about the permeable materials is whether the adhesive or potential contaminants from the fly ash will leach into the subsurface. It is important that leaching tests be performed to ensure contaminant immobility. An evaluation of the natural soils beneath the stairs is also needed to ensure they have sufficient capacity to accept the potentially high infiltration that will occur with the new steps.

SLA as a Component of a Green Roof System

The second project consisted of developing a ‘turnkey’ green roof system that can be use to convert conventional roofs into green roofs. The system was adaptable so that it can function on a wide variety of roofs. The student team devised a plan to design and implement a green roof, using the ‘turnkey’ system, on Tisch Library located in the center of the Medford/Somerville, MA campus of Tufts University. The pilot study’s goals are 1) to develop a reproducible turnkey system and 2) evaluate the different plant species and substrate combinations that optimize growth conditions as well as provide other benefits such as heat island reduction, storm water management, and insulation characteristics.

Background

Green roofs have many advantages over traditional roofs. Green roofs retain rainwater and reduce runoff during storms, filter particulates and other pollutants from air and rainwater, and reduce the urban heat island effect because they are much cooler than conventional roofs. Green roofs have significant economic benefits as well. They provide extra insulation to buildings, reducing energy costs, and usually last up to two times longer than traditional roofs. (Greenroofs.com, 2009 and Greenroofs.org, 2009)

Project Objective

The objective of the green roof project was to have it provide as many of these benefits, while at the same time enhance Tufts' image as a cutting-edge, environmentally-conscious university. The major scopes of work were 1) the development of a novel turnkey assembly system, 2) development of a green roof design for the Tisch Library roof, and 3) developing and implementing a pilot study of tray assemblies on the roof. Each of these scope items are discussed below.

Turnkey Assembly System

For the turnkey assembly system, the team researched green roofs to see what methods could be adapted for a final design. Different possible assembly methods were evaluated and a tray system was adopted for design and implementation. The modular capability of a tray system holds several advantages over loose-laid green roofs. For example, installers can assemble the trays away from the roof and place them in a greenhouse so that the plants can establish themselves in a controlled environment. The installer then can move the trays onto the roof once the plants are established. Tray systems also allow for flexibility because the trays can be moved. A tray system also allows easy access to the roof's waterproof membrane if any repairs need to be made. The initial tray design was similar to that developed by the project's consultant, Jeff Licht. The Licht turnkey tray system consists of planter trays (40 x 40 x 12.5 cm) with a permeable bottom. The tray depth can be increased to 30 cm with plastic inserts. The planter trays are made from recycled HDPE (High Density Polyethylene). Figure 3 illustrates the construction sequence of a walkable tray.

The tray system's stratification, from the bottom up, consist of the HDPE tray base (a in Figure 3), an absorbent layer (b), a non-woven geotextile filter + mesh layer (c), soil aggregate (d and e), a stiffing geo-grid (f), more soil (g), and finally plants (h). If the tray need not be walkable, then the stiffing geo-grid can be removed. The trays can be put directly onto a roof provided the

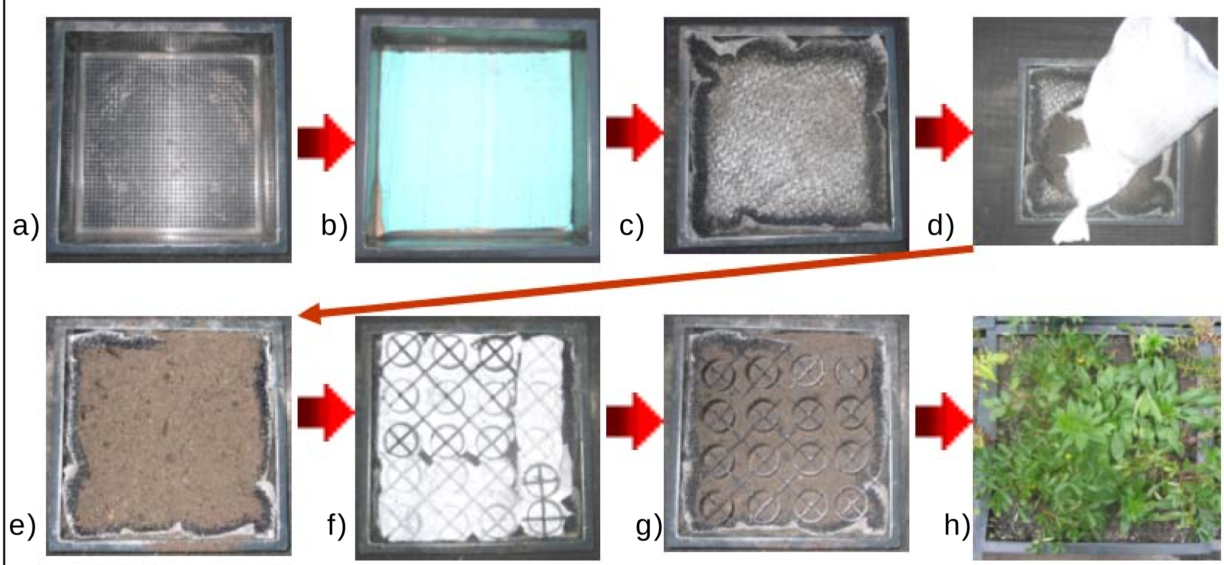


Figure 3 Steps in Development of Walkable Tray Assembly

roof is sufficiently waterproof and drainage from the bottom of the tray is not deterred. Alternatively, the trays may be placed on a drainage layer secured to the roof prior to tray installation. Such tray assemblies have estimated installation costs of $130 to $150 per square meter.

The project involved a preliminary evaluation of an alternative tray assembly in attempt to improve on the design of Licht tray, possibly integrating several layers. Designing new trays specifically for green roofs will allow the inclusion of other unique features. For example, the trays may be hexagon-shaped. Hexagon trays will create a honeycomb matrix when installed on a roof which may be more aesthetically pleasing than a square tray pattern.

In developing a final tray design, factors to consider include there durability, toughness, and stackability. Green roofs are known for their longevity; thus, the trays need to last for over 30 years. In addition, the trays must be strong enough for people to walk on. If the trays are stackable, shipping costs are greatly reduced. For tray composition, recycled HDPE appears to be the top choice, but further evaluation will be needed as to what method can be used to make the trays.

Green Roof Design
The site for project implementation of a green roof is the Tisch Library at Tufts University. Tisch Library, built in 1998, sits higher than most buildings on campus. The library is actually an expansion of the former library. The roof system of Tisch Library has two levels, an upper deck and lower deck. The upper deck is covered with concrete pavers and currently has three large soil beds in which to grow plants, currently grass. The larger lower deck of

Tisch is completely covered with a roof membrane. Both roof levels provide an excellent vantage point from which to view Somerville and Cambridge, as well as the Boston skyline. The lower roof deck is well suited for a green roof system because it is flat, large (approximately 4045 m^2 in area), has the structural integrity for additional loads from the green roof, and is already covered with a waterproof membrane which would provide protection from potential leaks. Figure 4 shows an aerial photo of the Tisch Library on Tufts campus. Note the three green pads on the northern, upper roof deck are part of the existing soil beds.

Figure 4 Aerial View of Tufts University and Tisch

The initial design for a green roof on Tisch Library was developed in consultation with Tufts University's Facilities Department. Discussion centered on the type of green roof system to install and how to implement the installation. Green roofs can be either an extensive or intensive green roof. Extensive green roofs usually consist of only a few plant species. They require very little maintenance. Intensive green roofs are composed of many different plant varieties. Intensive green roofs are usually more vibrant, but they require more maintenance than extensive green roofs and may require irrigation and replanting. Consideration was also given to methods for installing the green roof. Both a tray system and a loose-laid roof system were considered. Tray systems have the advantages listed earlier. Loose-laid systems also have advantages, especially on extremely large roofs because loose-laid roofs have fewer separate components. These discussions lead to the following design characteristics:

- The roof should be an extensive green roof. The size of the library roof, roughly 4045 m^2, suggests that an extensive green roof will greatly reduce the amount of maintenance work required. Because the roof is relatively high, there is no convenient way to access the roof if and when maintenance is necessary. An extensive green roof will still be aesthetically pleasing because it will convert the library roof into a large green field.

- A tray assembly system is preferred, particularly because the trays are an easy way to rearrange the roof. To convert the entire roof, approximately 23,000 trays are required. However, because the tray system is modular and replaceable, it will allow for segmented installation of the green roof and well as easy replacement of trays that have diseased or dying plants. Tufts Facilities Department can install a few trays at a time and then evaluate the roof performance before installing more trays.

Based on discussions with the Facilities Department, the team developed an initial roof layout for the library's new green roof, with the goal to create a park-like, walkable space. The first step to make the roof look more appealing was to incorporate paths to give the area structure and a flow of traffic. The next design principle was to incorporate flowering plants to represent garden areas around the perimeter of the roof. Finally, the size of the roof leads to a 5-phase plan for implementation. Each phase is meant to appear as a stand-alone project and continue to incorporate principles of design. The phases are centered around maintaining a central patio area for the first four phases. The fifth phase fills in the patio space and finishes the pathways. Figure 5 shows a proposed, 5-phase implementation process.

Pilot Study

An initial pilot study was conducted to evaluate plant survival; i.e., create a "default laboratory" for evaluating plant species and engineering characteristics of the tray system that enhance success of the green roof system. A pilot study area was created on a section of the library roof. Two main variables considered in the pilot study were soil or aggregate type and native versus non-native plants. The team wanted to test enough plants so there would be at least a few that would grow well, and because they wanted to test each plant in several different aggregates, it was decided to limit the number of different plant species to twelve.

The trays could use any type of aggregate and soil, from crushed stone to potting soil. However, to minimize the load applied to the roof by the trays, lightweight aggregates were incorporated as part of the soil. Plant selection also strongly depended on the success of the plants when placed on the roof. Plant appearance and aesthetics is also a design consideration, though this characteristic depends on preference rather than any quantifiable properties of the plants.

The most important criterion in aggregate selection was plant survival rate. The pilot study tested four different aggregates in the Licht tray assembly: a traditional, expanded clay/shale lightweight aggregate; synthetic lightweight aggregate (SLA) which is composed of a mixture of recycled plastics and coal fly ash; the third aggregate is pelletized HDPE; and the last aggregate is a

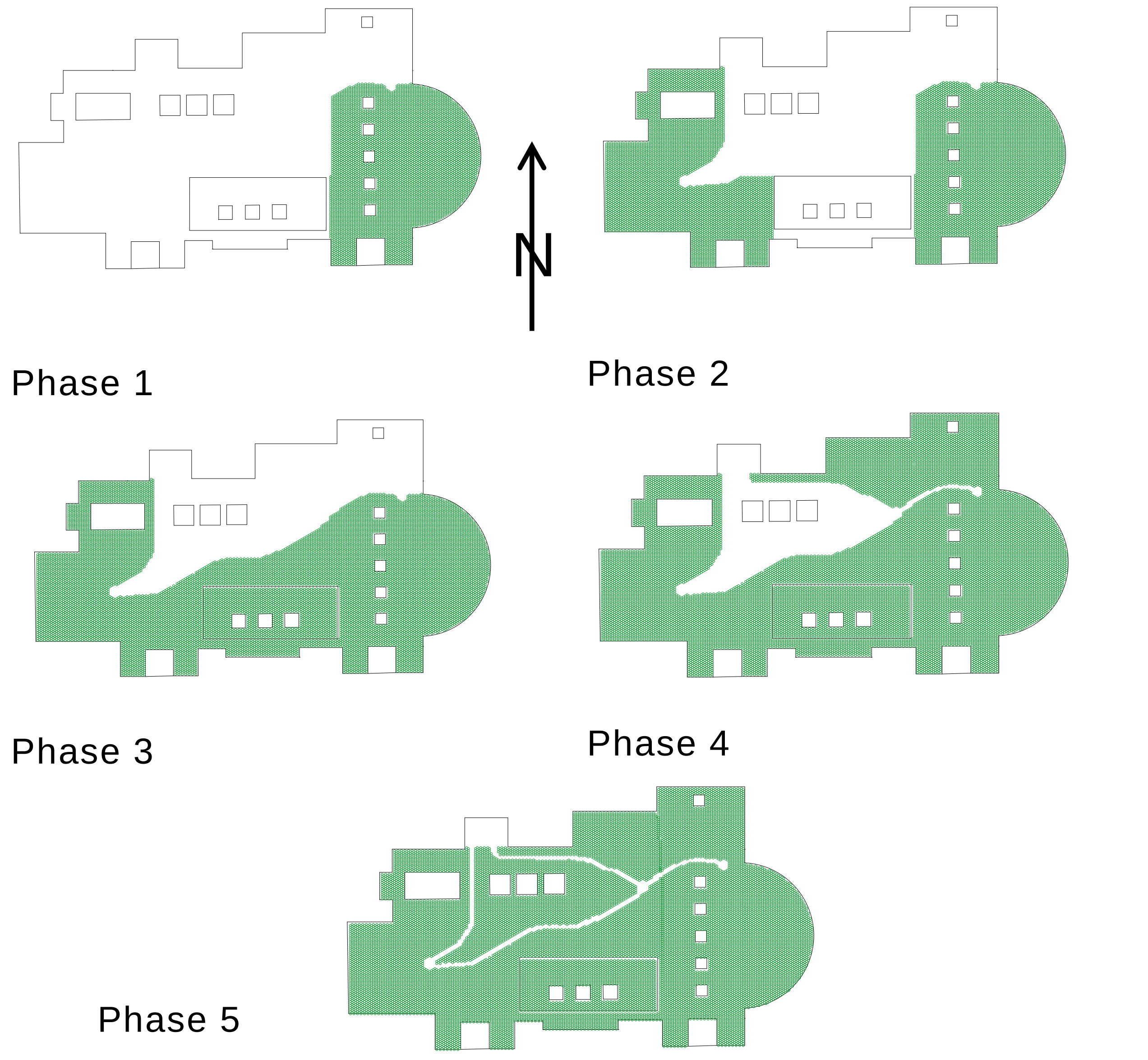


Figure 5 Five-Phase Implementation Strategy for Developing a Green Roof on Tisch Library

recycled asphalt shingle aggregate (RASA) consisting of granulated roofing shingles. All aggregates were of approximately the same maximum grain size (approximately 3 mm diameter), and twelve trays of each aggregate, one for each plant type, were created. Each aggregate was mixed with approximately 20% forest mulch to provide nutrients and organic matter for the plants.

Results and Recommendations

A qualitative evaluation of the various trays, based on how well the plants grew, indicated that plants with SLA grew best, followed by plants in RASA and then expanded clay/shale. The plants in pelletized HDPE did not grow well. Further studies are warranted to evaluate the proper plants as well as the long-term characteristics of the tray system. Specifically, future green roof applications should involve not only visual evidence of how well the plants grow in each aggregate but also physical measurements of temperature (above and below the trays), precipitation, and infiltration in and through the trays.

Summary

Previous work has shown that synthetic lightweight aggregates, SLA, can be utilized as an aggregate in traditional construction applications such as concrete and asphalt. The work presented in this paper provides evidence that SLA may also have other applications, specifically as aggregate in pervious pavement/concrete designs or as a lightweight aggregate in green roof applications – both sustainable engineering applications. Alone, SLA is a "green" product having been created from recycled plastics and coal fly ash, so the use of it in sustainable design and engineering only enhances its value.

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