

**Building Nature Conservation:
Masonry From Alkali-Activated Industrial Waste
& The Economics of Ecosystem Services**

by

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B.S. Civil Engineering
Tufts University (2013)

Submitted to the Institute for Data, Systems, and Society
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2019

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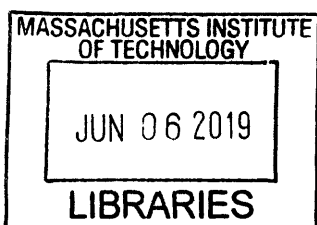
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Abstract

India's soaring population elicits increased demand for construction materials and waste generation. Incumbent materials such as the fired clay brick demand high energy manufacturing processes and pose serious environmental and human health hazards. Separately, the landfilling and illegal disposal of industrial waste is unsustainable and growing rapidly along with population. To address both of these issues, we have developed a brick composed of 90% industrial waste that is superior to a traditional fired clay brick in environmental impact and comparable in cost while meeting the physical properties that structural code mandates. By transforming industrial waste into sustainable building materials through alkali-activation, we propose a solution to help alleviate the environmental, ecological, and human health impacts of India's housing crisis. Surge in material use leads not only to environmental impact from processing, manufacturing, and transportation, but also imposes an ecological burden via extraction of raw materials. This ecological deterioration can be accounted for by imputing values for the unmarketed values of ecosystem services—benefits to humans derived from working ecosystems—and captured in the material's price. This thesis looks at the life cycle impact of the novel alkali-activated masonry and traditional building materials, and also conducts an ecosystem service valuation to shed light on hidden ecological costs associated with material extraction. In concert with the technical analysis, this thesis proposes a framework to streamline the acknowledgment of environmental services into policy which could assist in ousting incumbent materials and the environmental harm associated with their development. Dormant potential lying in landfills can become an active solution to the region's population problem.

Thesis Supervisor: Elsa Olivetti
Title: Principal Investigator, Olivetti Group
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Acknowledgments

Thank you Elsa, Frank, Barb, fellow TPPers, and my family.

“In wildness is the preservation of the world”
—Henry David Thoreau

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Part I

Masonry from Industrial Waste

1 Introduction

Rapid population growth in India has led to a steep rise in both industrial activity and the demand for construction materials. Incumbent building materials are environmentally and ecologically burdensome, and the current practices of industrial waste disposal are not sustainable. To address both of these issues, we have developed a viable construction material made of 90% industrial waste, whose use could both reduce the environmental impact of India's housing crisis and alleviate landfills by diverting waste streams to beneficial use.

India holds over 1.3 billion people, and is projected to become the most populous country in the world before 2030.^{1,2} To accommodate such a vast increase in population, India's housing stock will need to be quintupled from 2005 to 2030. This will create a surge in materials' demand and use, and the scale of the environmental impact from this phenomenon will heavily depend on the choice of building material. The construction sector in India is responsible for 22% of carbon dioxide emissions,³ and housing accounts for 60% of construction material consumption.⁴

The fired clay brick is ubiquitous on the Indian landscape—it is the most used building material in the country with upwards of 150 billion bricks produced annually⁵—about 92% of masonry units⁶— and its incumbency sets its dominance to continue throughout the housing expansion. The desirability of the fired-clay brick stems from its low cost and local availability of clay, but through an environmental lens, this low price is only due to negative externalities that are ignored in the market. Manufacturing fired clay bricks consumes extraordinary energy, creates significant air pollution, and degrades natural ecosystems. To fire bricks, requires kiln temperatures to reach over 1000°C, which makes the creation of clay

bricks to be the third largest consumer of coal in India.⁵ Outdated kiln technology leads to the outflow of carbon monoxide, sulfur dioxide, nitrogen oxides, black carbon, particulate matter, and carbon dioxide.⁶ On the ecological side, clay extraction causes the removal and degradation of topsoil, which underpins an ecosystem. This causes significant losses of ecosystem services.⁷ These issues have incited the need and pursuit of a less environmentally burdensome alternative to the traditional fired clay brick, without sacrificing quality or hiking cost.⁸

In tandem with unprecedented population growth and the associated construction material demand is rapid industrial growth in India. This increased industrial activity causes a surge in industrial waste creation—most of which is landfilled or disposed of illegally—which results in environmental and human health hazards. This thesis will focus on one waste stream in particular as it is a crucial ingredient to our novel masonry—biomass ash. Because much of rural India lacks energy access, many small and medium factories produce their own energy by burning leftover agricultural matter in industrial boilers, which creates a byproduct of biomass ash. This process is quite widespread: primary solid biofuels, such as rice husk, sugar cane bagasse, straw, wood, and other plant matter, are responsible for 35% of total energy generation in India and other developing countries.^{9,10} Additionally, industrial biomass incineration for heat and power is predicted to triple by 2035 compared to 2008 levels.¹¹ Currently, this biomass ash is either landfilled or dumped illegally on fields and farmland. Landfilling industrial waste is not a sustainable practice and is putting increasing pressure on the environment, and disposing the waste illegally leads to fine ash particles polluting the air, exacerbating environmental hazards and endangering human health.

It could be that two of the problems caused by India's population boom—increased building material demand and increased industrial waste—could be solutions to each other. By using industrial waste to create a more environmentally-friendly alternative to the fired clay brick, environmental impacts from industry and housing are alleviated. This is made possible by a process called alkali-activation, through which inert industrial wastes can be-

come reactive and form a cementitious binder. After agricultural residue is incinerated, silica and alumina are left in the biomass ash. This can then be dissolved via an alkaline solution, and in the presence of calcium, an aluminosilicate-based microstructural matrix such as calcium silicate hydrate (C-S-H, the main hydration product of Portland cement¹²) or calcium aluminosilicate hydrate (C-A-S-H) forms during curing at ambient temperature. The final product is a masonry brick with a structural binder similar to that in concrete, made chiefly of industrial waste, without any energy-intensive firing. Previous studies^{7,13} have shown that the life-cycle impact of a traditional fired clay brick is much higher than that of an alkali-activated brick derived from industrial waste.

The development of an alkali-activated brick that satisfies structural code requirements, is significantly less environmentally burdensome than incumbent materials, is comparable in cost to incumbents, and is robust in design has been the cumulative effort of over five years of work at MIT. Particularly, achieving satisfactory water absorption and ensuring robustness of design have been significant obstacles.

Variation in biomass ash, reactivity of precursor materials, and building codes intended for incumbent materials all posed challenges to creating a viable brick made of industrial waste. The content of biomass ash fluctuates seasonally, geographically, and based on the temperature the boiler burned the plant residue. Most rural industrial boilers burn inefficiently which leaves a varying amount of unburnt material, and in combination with variable availability of plant matter due to growing seasons, this results in an ash that varies in physical and chemical properties.¹³ A significant amount of agricultural residue can remain unburnt after incineration due to boiler inefficiencies, and this unburnt carbon in the biomass ash leads to less reactive material and increased water absorption.¹⁴ The reactivity of the ash depends on the amount of reactive amorphous silica and alumina, calcium and iron content, unburnt material, and particle size.¹³ To provide an accessible alternative to fired clay bricks, all ingredients should be available regionally and year-round. Variation in other industrial waste streams, such as crushed brick and steel slag, are also concerns—although these tend

to not vary in composition as much as the biomass ash. A significant portion of this study was devoted to ensuring robustness of brick design.

1.1 Structural Requirements

The Bureau of Indian Standards dictates that fired clay bricks must pass requirements based on dimensionality, compressive strength, and water absorption.¹⁵ Dimensionality and compressive strength have not been issues, but achieving satisfactory water absorption levels has been a huge barrier to implementation of alkali-activated bricks. They have continually exhibited water absorption values that are too high for the Indian Standard which mandates a maximum of 20% by weight and minimum strength of 10 Mpa for Class 10 bricks, which are commonly used and the classification that we seek. Poor water absorption properties correlate with immediate strength loss while saturated due to an increase of internal stresses (hydrostatic forces) when compressing the brick.

High water absorption can also cause long term durability issues for several reasons. Through cyclical saturation and drying from environmental causes such as groundwater, stormwater runoff, or precipitation, masonry materials can lose structural capacity through various processes. Key examples are the freeze-thaw cycle, cryptoflorescence, salt hydration, and, in the case of alkali-activated bricks, desorption.^{16,17} Water absorption is the driver for all of these activities, and the percentage (by weight) of water absorbed should determine the magnitude of their effect on masonry strength. One of the main criteria aimed for by the construction materials industry is durability, which plays a major role in controlling serviceability.¹⁹

Desorption affects the structural integrity of the brick's binder matrix because of the differential in pH between the alkali binder pore solution and the neutral environmental fluid.²⁰ As water enters the brick's structural matrix through invasion percolation, a leaching process is initiated which can weaken the system's compressive strength capacity. This process should be magnified by higher water absorption.

Other phenomena can cause high internal stress due to repeated exposure to water, too. Formation of cryptoflorescence can trap water in masonry pores, causing stresses when the brick is heated and the coefficient of thermal expansion of water is greater than that of the masonry. Hydration of salts that entered the masonry capillaries via water absorption can also cause high internal stresses due to their crystallization pressure or thermal expansion. These effects can happen in tandem, and as cryptoflorescence and salts accumulate in the brick's pores and capillaries with repeated exposure to groundwater, stormwater, and precipitation, the magnitude of their impact can increase.¹⁷

1.2 Strategies to Reduce Water Absorption

We implemented several strategies to lower water absorption in the bricks. One method was compressing the bricks to a higher pressure when forming, which should lead to a denser structure with less pore space—but we hit a local constraint at 35 Mpa, which is the maximum most manual pressing machines in India can provide.¹⁸ Reducing the ash content was another strategy, as the ash was characterized to be very porous, but there is a limit here, too—the ash provides the silica and alumina required to create C-S-H, and lowering the ash content too much could endanger the structural integrity of the brick.

1.2.1 Water repellents

A third solution was to add a hydrophobic admixture that would repel water from pores. Some of the brick designs were treated with a silicon water repellent, leading to the protection of the structure from water absorption and surface contamination by pollutants. Silicon water repellents have excellent properties such as breathability, waterproofness, colorless, high penetration depth, and resistance to chloride ion ingress.²¹ Silicon-based water repellents are used as an additive in bricks, and it can be present in two forms: admixture (added while mixing the precursor materials) or coating (added after the curing phase). The difference between silicon water repellents and other waterproofing additives lies in how

they function: while other additives fill the pore, or seal it, silicon-based additives form a hydrophobic layer on the surface of the pore, not blocking or sealing the pore, consequently keeping the same appearance of the initial material.²¹ There are also concerns that coating can also cause problems with adhesion to mortar,²² and that if the bricks are chipped, water may enter the pores and have trouble exiting, creating internal pressures. Silicon-based hydrophobic additives can belong to two different families: silane (Si-Si)²³ or siloxane (Si-O-Si),²⁴ and in this research, we used a siloxane admixture known as Silres BS 1703 (manufactured by Wacker Chemical).

1.2.2 CSEBs

Another way to reduce water absorption is to look at the bricks through the lens of compressed stabilized earth bricks (CSEBs), and employ strategies used to reduce porosity in those materials. The alkali-activated bricks are very nearly CSEBs and could be classified as such—as they are compressed to 35 Mpa the ash, clay, slag, and lime compact similarly to how soil would in CSEBs, and they are stabilized through the formation of cementitious binders (C-S-H and C-A-S-H) similarly to how CSEBs are stabilized with the addition of Portland cement. Water absorption is an issue in CSEBs because moisture content affects the durability and strength development of bricks, significantly impacts long term structural performance, and influences their ability to adhere to mortar.²⁵ In CSEBs, water absorption and porosity has been observed to increase with clay content and decrease with cement content, so one method to lower absorption is to foster a higher formation of CSH to fill pores.²⁶ Another method employed on CSEBs that we also used is to increase compaction pressure to minimize void space.²⁷

The focus of this years-long work has been to develop a masonry product which reduces the impact of landfilling industrial waste and decreases the reliance on fired clay bricks. This thesis's contributions are the recipe and results of a viable brick design that, for the first time, satisfies building codes by achieving appropriate strength and water absorption, has a

significantly lower environmental impact compared to incumbent materials, and is robust in design.

2 Methods

The alkali-activated bricks are made of biomass ash, hydrated lime, sodium hydroxide pellets, municipal water, and also either clay, steel slag, or calcined clay (crushed brick). Two of the biomass ashes used in this thesis's data was obtained from paper mills in the Uttar Pradesh region of India—specifically, Silverton and Sidhali—and one from Texas which is composed primarily of rice husk ash. Collaboration with these factories has allowed us to characterize several batches of biomass ash that vary by boiler type, season, biomatter content, and incineration temperature. This mixed feedstock approach allows us to investigate the robustness of these waste streams.

The clay was also obtained from the local northern India region, extracted from fields nearby the paper mills in Muzaffarnagar. Hydrated lime was acquired from Madigan Lime Corporation in Massachusetts. Sodium hydroxide pellets were obtained from Sigma Aldrich. De-ionized water was used to create the activating solution, and unfiltered tap water was used in water absorption tests to best mimic field conditions in India. The steel slag used in this study was produced via a ladle metal furnace during steel production, and was obtained from ArcelorMittal. Calcined clay was made in the lab by heating clay to 1000°C for one hour, and was made to mimic crushed clay brick—a common waste material in India and elsewhere.

To characterize the precursors and binder, several methods were used, including X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), nitrogen sorption tests, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), thermogravimetric analysis (TGA), inductively coupled plasma optical emission spectrometry (ICP-OES), particle size distribution (PSD), leaching tests,

loss on ignition tests, compressive strength tests, and water absorption tests.

2.1 Creating alkali-activated bricks

For sample preparation, biomass ash and all other precursors were mechanically ground and sieved so that no particles were larger than 500 μm . Sodium hydroxide solution was made a day in advance, as its creation is an exothermic reaction and requires time to cool to ambient temperature.

All dry ingredients (ash, lime, and either clay, calcined clay, or steel slag) were weighed, placed in a bowl, and mixed together using an electric mixer for five minutes at a low speed. The sodium hydroxide solution was then added to the homogenized dry powder and all was mixed at a medium speed for seven minutes, at which point the loose binder was lifted from the bowl edges by hand, and was then mixed for another seven minutes on a high setting.

The wet binder was then pressed into 200 gram cubic brick samples using a hydraulic press. This compaction was done with a fixed loading rate of 15,000 N/min, in a compaction mold with inner dimensions of 50 mm x 50 mm. The height of the samples varied from 40 mm to 45 mm due to sample composition. After compaction, samples were wrapped in plastic sheeting and put in an oven to cure at 30°C for seven days. All experiments were performed in triplicate.

2.2 Performance analysis

2.2.1 Compressive Strength & Water Absorption

Compression tests were done with a hydraulic press at a loading rate of 15,000 N/min to determine compressive strength. Samples were completely dry when tested.

Water absorption tests were done largely in compliance with ASTM C140²⁸ intended to instruct the testing of concrete masonry units. After curing, samples were removed from plastic wrap and placed in an oven at 110°C for two days. Samples were then submerged in

ambient temperature water for a minimum of 24 hours, and then weighed (W). The samples were placed back into an oven at 110°C for an additional two days (longer than ASTM recommended to ensure alkali-activated bricks were completely dry), and then weighed (D). Early in the experiment, one sample was dried at 55°C for six days rather than 110°C for two days (this is noted in Table 2). It should be noted that research²⁹ has shown that exposing cementitious materials to 110°C can stop the hydration process, and therefore hinder C-S-H formation. Water absorption (WA) was then calculated by the following formula:

$$WA = \frac{W - D}{D} * 100$$

2.2.2 Cost

According to the Government of India Central Public Works Department,³⁰ the cost of a fired clay brick in northern India is about \$0.064 (4.5 INR). One of the goals of this research was to develop a brick derived from industrial waste that was comparable or cheaper than incumbent materials, and so the cost for our alkali-activated bricks was approximated based on market values of materials. Table 1 below displays the market values used in the calculation of our brick designs. Waste materials that are currently landfilled were assigned a price of zero. Labor wages were based on clay brick makers in Muzaffarnagar, and assume use of automated machinery.³¹

2.2.3 Life-Cycle Assessment

To quantitatively assess the environmental burden of the alkali-activated bricks, we performed life-cycle assessments (LCAs). Although previous research had shown that fired clay bricks have a higher impact than alkali-activated bricks, the bricks in this study are comprised of different mix designs. Furthermore, when optimizing within this study's constraints of strength, absorption, cost, and environmental impact, LCAs are an effective tool to differentiate impact among different brick designs.

Table 1: Market Values of Materials

Material	Market Price	Unit
Biomass Ash	\$0	kg
Hydrated Lime	\$0.073 ¹⁸	kg
Municipal Water	\$0 ¹⁸	kg
Sodium Hydroxide	\$0.87 ¹⁸	kg
Indian Clay	\$0.0073 ¹⁸	kg
Crushed Brick	\$0	kg
Steel Slag	\$0	kg
Silres (additive)	\$11*	kg
Electricity**	\$0.063 ³²	kWh
Labor	\$0.003 ³¹	per brick

*This is a typical market price for a siloxane additive when bought in bulk, not the price for Silres BS 1703 specifically. For Silres product prices, contact Wacker Chemical.

**Electricity used for compaction for all mixes and in heating of carbon-reduced (CR) mixes

The life cycle impact assessment was conducted using openLCA 1.7 software, developed by GreenDelta.⁵⁸ All inventory materials and their associated upstream impacts were derived from the ecoinvent 3.4 cut-off database, and the analysis was done using IMPACT 2002+ (Endpoint) methods. Processes were represented as unit processes rather than system processes, and providers were chosen to be a general rest of world (RoW) source, as Indian-specific precursor materials were not available. Another important assumption was that because biomass ash is currently a waste product that is landfilled, it was categorized as an elementary flow with no associated upstream impacts.

The temporal boundaries of this study are bound between the acquisition of materials, whether through raw materials extraction or acquisition via industrial waste streams, and the implementation in construction. The long-term behavior and lifespan of the alkali-activated bricks is assumed to be similar to fired clay bricks for the purposes of this assessment. This study pertains to only the direct and conventional uses of the bricks—materials acquisition, processing, and manufacturing. Although incineration of biomass such as rice husks and sugar bagasse to produce electricity certainly has environmental implications, this study only accounts for the use of biomass ash as if it were an unprocessed, raw material. Other

industrial wastes that are discussed reside within the same assumption. End-of-life aspects are not included. The functional unit is volume of masonry (one brick).

Because the clay and biomass ash are sourced locally, it is assumed these materials are transported approximately 50 kilometers via unspecified trucks. Crushed brick and steel slag are assumed to be available locally, so they were also assumed to be transported 50 km. Similarly, the lime was assumed to be transported 100 km, and the sodium hydroxide 200 km via trucks. The tap water is assumed to be available on site. There is also a small amount of electricity used in the compaction process, assumed to be 0.00875 kWh per brick (for compaction to 35 Mpa).

Carbon-reduced ash mixes were modeled assuming that biomass ash was delivered from the mill to a brick manufacturer after a typical incineration process. The manufacturer would then have to burn the ash again to reduce carbon content, consuming a significant amount of electricity. If the mill were to manufacture the bricks themselves and burn more carbon during incineration, or they were able to more efficiently incinerate the ash through new processes, the impact from carbon reduction would significantly decrease—but for the purposes of this thesis, the higher-impact scenario is considered.

3 Results

The results of the compressive strength testing, water absorption testing, life-cycle assessments, and cost calculations are displayed in Table 2 below. All of the alkali-activated brick designs exceeded the required minimum compressive strength of 10 Mpa for Class 10 bricks. Only two mixes had satisfactory water absorption levels—mixes G and N—which were comprised of 50% carbon-reduced ash, 40% clay, and 10% lime, with Silres BS 1703 water repellent added. Mix G contained Silverton ash and mix N contained Sidhballi ash. The carbon reduction and additive consequently increased the environmental impact and cost, but the life-cycle assessment still shows a considerable decrease in comparison to a

traditional fired clay brick—140 versus 181 points. The cost per brick for mixes G and N is 66% higher than a traditional clay brick—\$0.106 versus \$0.064—primarily due to the addition of the siloxane additive. Eight of the mixes had environmental impacts that were about 30% than that of a fired clay brick, and all mixes without the water repellent additive were twice as cheap as a fired clay brick. The lime and sodium hydroxide dominated the price in all mixes without Silres, composing 52% and 35% of the cost, respectively, in mixes with waste aggregates (A, I, J, K, L).

Mixes M and L are also notable—M had a water absorption level of 20.6%, just over the 20% limit, and achieved this without requiring carbon reduction of its ash. This lowered its LCA impact to only 92 points, and its cost by half a cent per brick as well. Mix L performed the best among bricks without the siloxane additive. It also did not require carbon reduction, and its additive was steel slag—an industrial waste, compared to clay which has to be extracted from the ground. Because mix L was comprised of 90% industrial waste and did not require additives or alterations, its cost is less than half of traditional fired clay bricks, and its environmental impact less than a third of the incumbent material. This is despite the bricks having to be slightly heavier, as steel slag is denser than clay or crushed brick, and so per the same volume (the functional unit in the LCA analysis), there is more material.

Figure 1 displays the mixes on performance axes of water absorption, environmental impact, and cost—strength was not included for clarity as all mixes had sufficient strength.

	Mix Design								Properties			
	Ash	Lime	Aggregate	NaOH	L/S	Additive	Compaction	Water Absorption	Strength	LCA Impact	Cost	
A	50 SDBL	10	40 steel slag	0.5 M	0.3	-	35 Mpa	28.7%	32.7 Mpa	56.10	\$ 0.030	
B	50 SDBL	10	40 clay	0.5 M	0.3	-	35 Mpa	28.8%	34.5 Mpa	56.17	\$ 0.034	
C	50 TEX	10	40 clay	0.5 M	0.3	-	35 Mpa	29.0%	34.8 Mpa	56.17	\$ 0.034	
D	50 SLVT	10	40 clay	0.5 M	0.3	-	35 Mpa	28.3%	33.4 Mpa	56.17	\$ 0.034	
E	50 SDBL	10	40 clay	0.5 M	0.3	Silres (0.23%)	35 Mpa	20.9%	34.1 Mpa	90.84	\$ 0.100	
F	50 SLVT	10	40 clay	0.5 M	0.3	Silres (0.23%)	35 Mpa	21.9%	36.0 Mpa	90.84	\$ 0.100	
G	50 SLVT CR	10	40 clay	0.5 M	0.3	Silres (0.23%)	35 Mpa	15.5%	32.5 Mpa	139.66	\$ 0.106	
H	50 SLVT CR	10	40 clay	0.5 M	0.3	-	35 Mpa	26.8%	37.8 Mpa	104.94	\$ 0.041	
I	50 SDBL	10	40 calcined clay	0.5 M	0.3	-	35 Mpa	34.6%	18.6 Mpa	52.09	\$ 0.028	
J	40 SDBL	10	50 calcined clay	0.5 M	0.3	-	35 Mpa	31.1%	20.3 Mpa	52.09	\$ 0.028	
K	30 SDBL	10	60 calcined clay	0.5 M	0.3	-	35 Mpa	25.7%	29.5 Mpa	52.09	\$ 0.028	
L	30 SDBL	10	60 steel slag	0.5 M	0.3	-	35 Mpa	23.5%	27.0 Mpa	56.10	\$ 0.030	
M	40 SDBL	10	50 clay	0.5 M	0.3	Silres (0.23%)	35 Mpa	20.6%	29.8 Mpa	91.87	\$ 0.101	
N	50 SDBL CR	10	40 clay	0.5 M	0.3	Silres (0.23%)	35 Mpa	18.6%	14.8 Mpa	139.66	\$ 0.106	
O	50 SDBL CR	10	40 clay	0.5 M	0.3	-	35 Mpa	29.0%	15.3 Mpa	104.94	\$ 0.041	
Fired Clay Brick, at minimum standards:								20.0%	10.0 Mpa	180.89	\$ 0.064	

Table 2: Performance of all tested mix designs. SDBL refers to Sidhbali ash, SLVT to Silverton ash, TEX to Texas ash, and CR to Carbon Reduced ash. LCA impact is in the unit of points. L/S refers to the liquid-to-solid ratio. Subsequently, mix designs will be referred to by their alphabetical designation (A, B, etc.). It should be noted that mix A was dried at 55°C for six days rather than 110°C for 2 days due to previous experimental standards.

Performance of AA bricks in absorptivity, impact, & cost

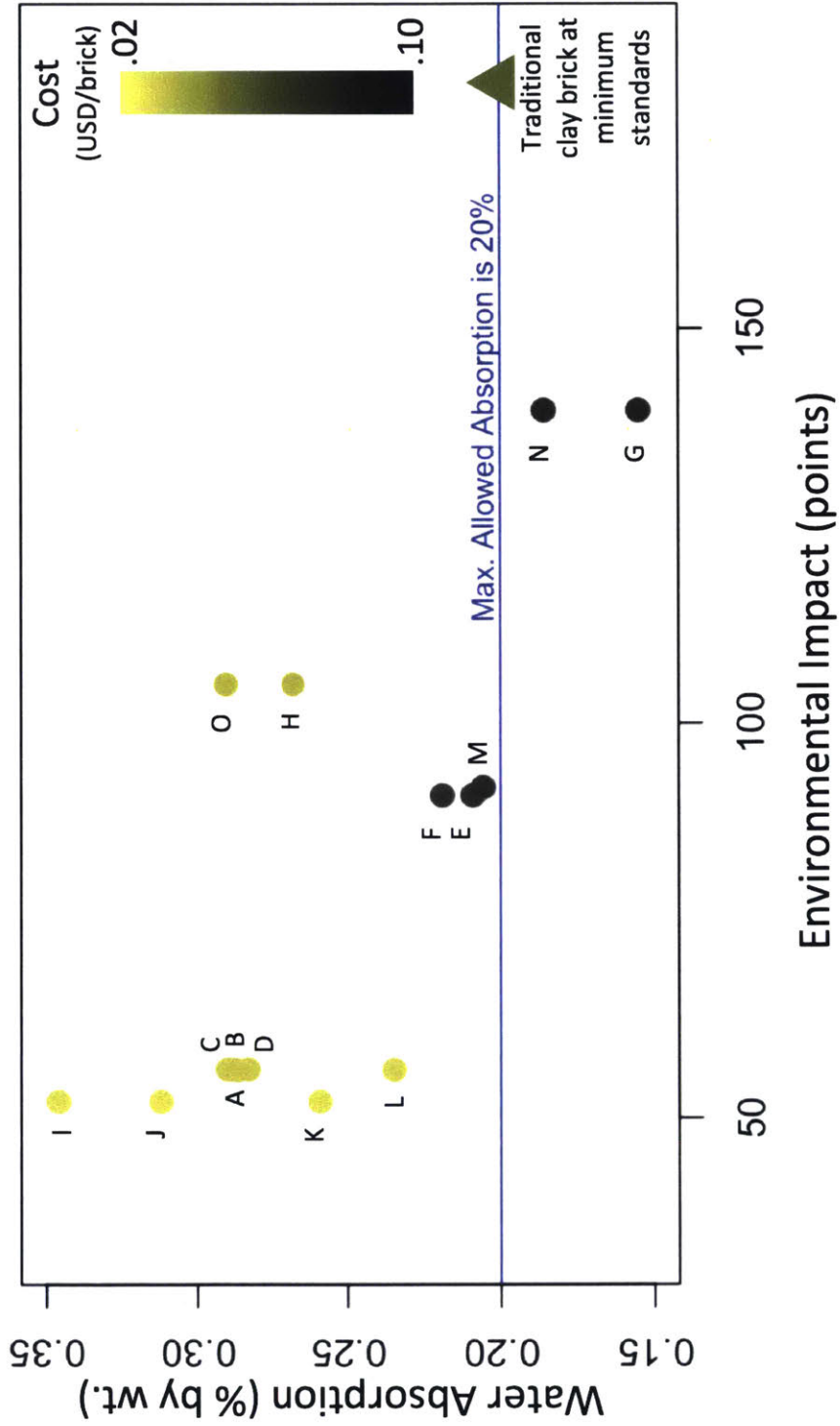


Figure 1: Brick performance as quantified by water absorptivity, environmental impact, and cost

The mixes showed robustness in ash type across both strength and water absorption and, to a lesser extent, robustness in aggregate type across the same parameters. Mixes B, C, and D were similar except for variation in ash (Sidhballi, Texas, and Silverton, respectively) and exhibited less than 1% variability in water absorption and less than 5% variability in compressive strength. Mixes A, B, and I were similar except for aggregate type (steel slag, clay, and calcined clay imitating crushed brick, respectively) and showed similarity of strength, but while the mixes with steel slag and clay were only 0.1% apart in water absorption, the mix with calcined clay was 6% higher. Figures 2 and 3 show the robustness of ash and aggregate, respectively.

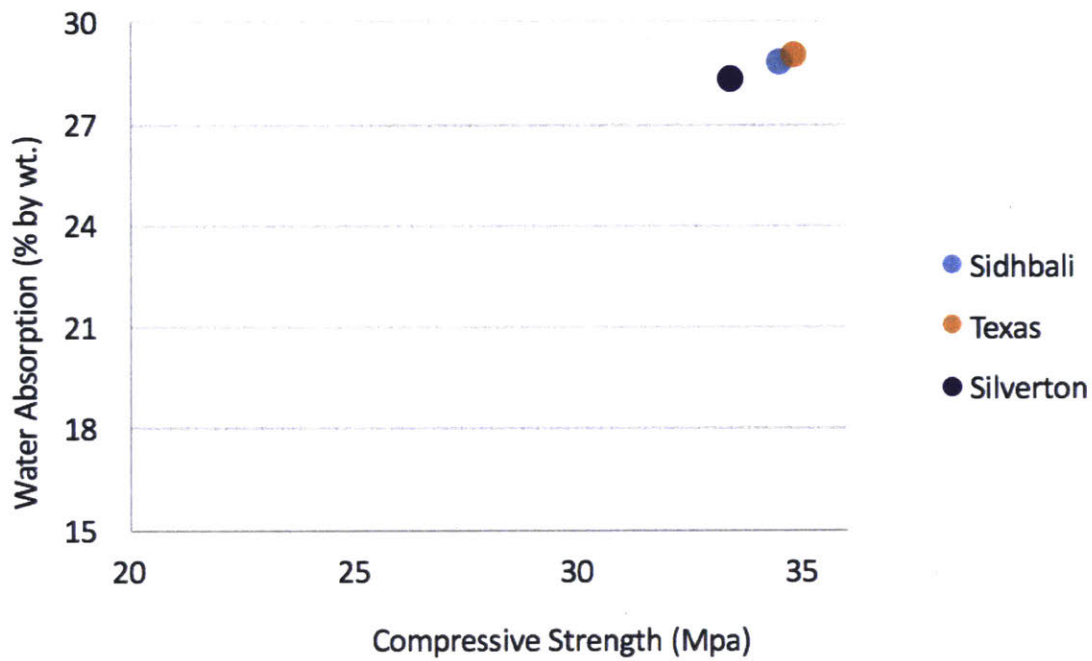


Figure 2: Robustness of ash

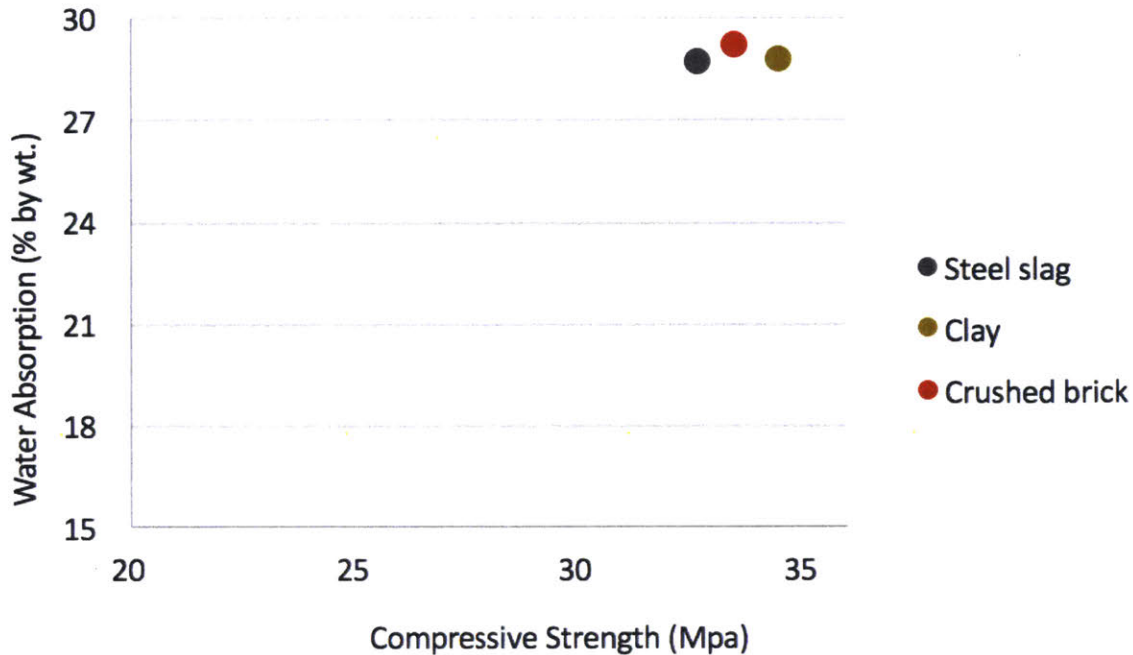


Figure 3: Robustness of aggregate

Ash content was reduced throughout mixes I, J, and K to test if the porous amorphous silica that dominates the ash was a primary factor responsible for water absorption. The results show that reduction in ash content led to decreased water absorption—from 34.6% to 31.1% to 25.7% as the ash content was reduced from 50% to 40% to 30%, respectively. Because their strengths actually increased as ash content decreased, it appears that the silica is not the limiting factor in the formation of C-S-H even at 30% ash levels. The gain in strength may be due to the relative compressibility of calcined clay versus biomass ash.

These three mixes—I, J, and K—can also be analyzed through the lens of compressed stabilized earth bricks (CSEBs). With constant compaction pressure and, from the above reasoning, similar C-S-H formation, pore space is the main factor that changes through these designs. Therefore, it can be inferred that the C-S-H content-to-pore space ratio increases as ash content decreases, and is highest in mix K and lowest in mix I. The trend shows that higher binder: void ratio shows lower water absorption and higher compressive strength.

The water-repelling additive (Silres BS 1703) exhibited effectiveness in reducing wa-

ter absorption in the alkali-activated bricks without compromising strength. As shown in Figure 4, mixes with Silres BS 1703 had a significant reduction in absorptivity compared to their counterparts with no additive. Mixes B and D experienced a reduction from 28.8% and 28.3%, respectively, to 20.9% (E) and 21.9% (F), respectively. Furthermore, Silres BS 1703 was observed to have a more dramatic effect in carbon-reduced mixes—this was tested because research³⁴⁻³⁷ has theorized that air-entraining agents can interact negatively with carbon. In the carbon-reduced mixes, water absorption went from 26.8% (H) to 15.5% (G). The effectiveness of Silres BS 1703 and its interaction with carbon is exhibited in Figure 5.

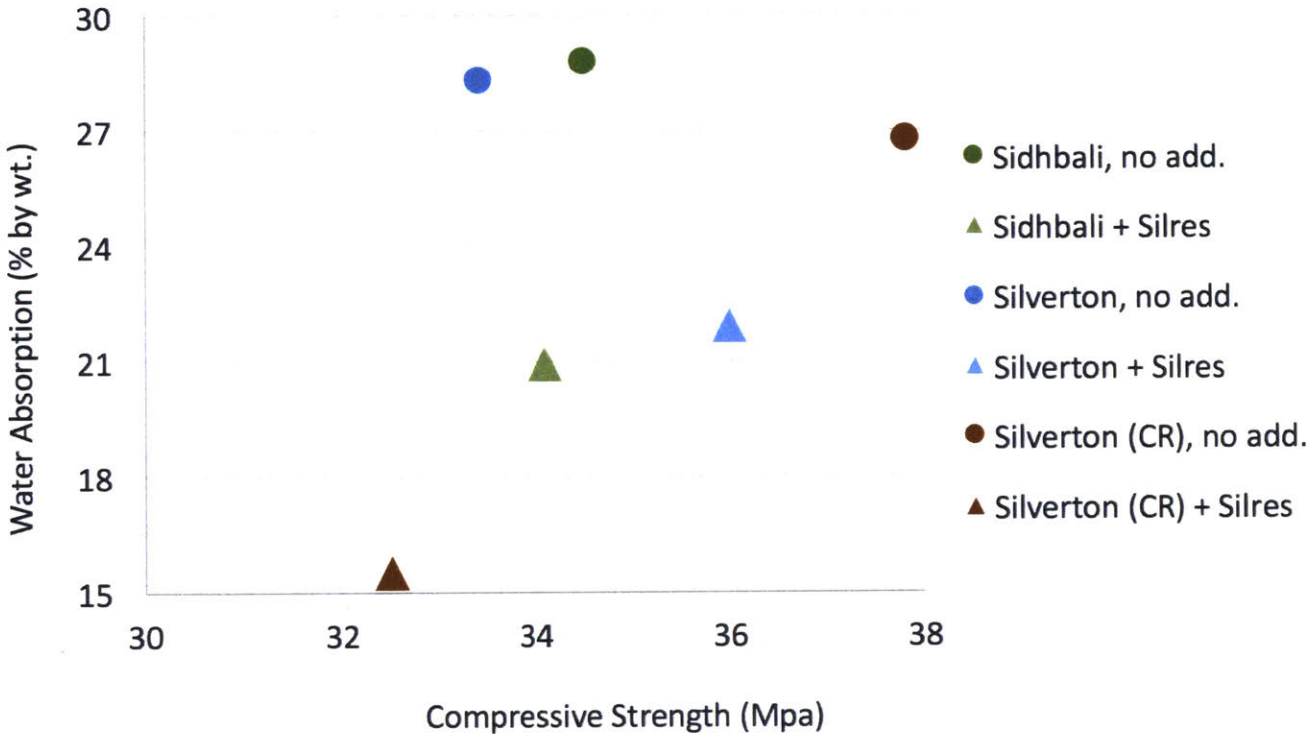


Figure 4: Effect of water-repelling additive

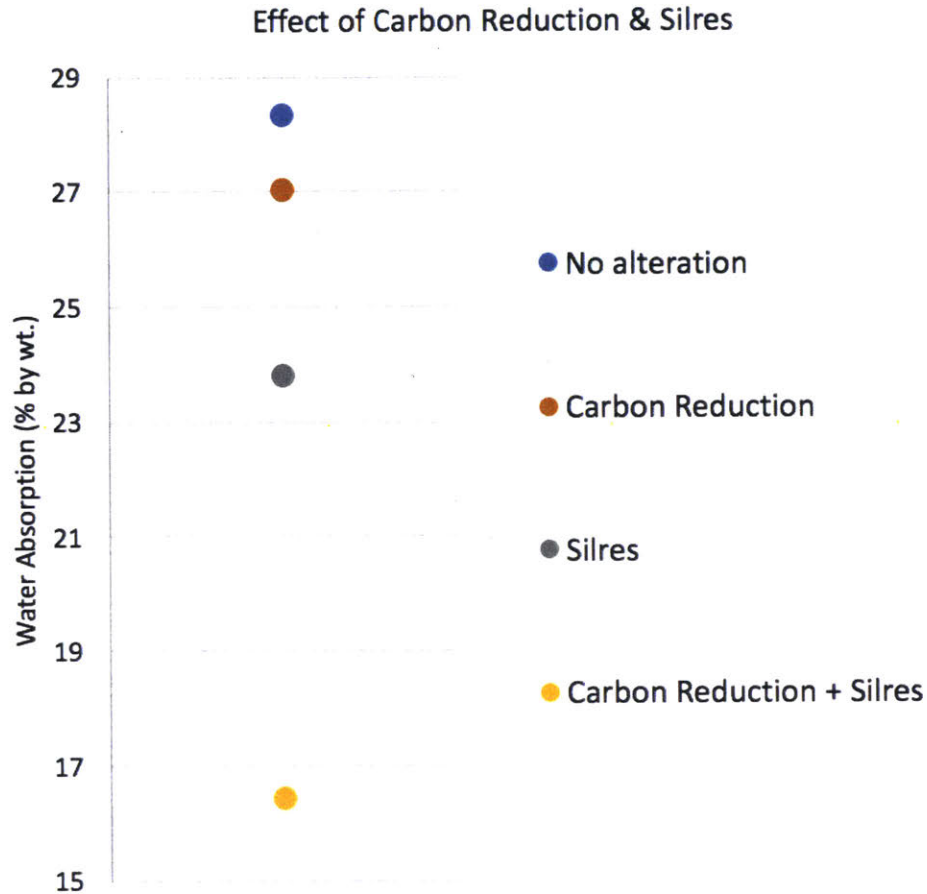


Figure 5: Interaction of Silres (siloxane additive) and carbon

A tangential experiment was performed to look at the long-term durability of the alkali-activated bricks when subjected to multiple wet-dry cycles. Samples consisting of 50% Silvertown ash, 40% clay, 10% lime, 1M NaOH, 0.28 liquid-to-solid, and compacted at 20 Mpa exhibited a water absorption of 27.3%. The bricks were tested for strength after 28 days of curing and then after 14 wet-dry cycles, along with a control group that did not undergo cycling. Results showed that after cycling, samples lost 22.3% of compressive strength compared to their non-cycled counterparts.

4 Discussion

4.1 Robustness

Robustness was a major element in the design of these alkali-activated bricks, as the industrial wastes that dominate their composition—biomass ash in particular—vary in physicochemical properties due to seasonal and geographical fluctuation in feed stock, factory process, processing temperature, quenching or cooling methods (for slags), and other factors. Ideally, an alkali-activated brick recipe would allow for different ash and aggregate types so manufacturers would not be limited by local or seasonal availability. From this research, it appears that though biomass ash varies in composition, as long as it has sufficient silica it can comprise a significant portion of the mix. Clay and steel slag had similar effects on water absorption and strength, although only one type of slag was tested, and so more testing would have to be done to ensure sufficient structural properties of bricks containing other slags. It is encouraging, though, that from previous research, not a significant amount of C-S-H precursor material was extracted from any of the tested aggregates, so this broadens the scope of acceptable materials—as long as they compress relatively well to reduce pore space and limit water absorption, they could be suitable aggregates.

4.2 Current Indian Bricks & Industry Testing

Although the goal was to satisfy Indian Standard code requirements pertaining to Class 10 bricks, all mixes achieved strengths greater than 10 Mpa. A brief comparison of the strengths of common fired clay bricks in different Indian regions^{38,39}—shown in Table 3—shows that almost all the alkali-activated brick mixes have superior compressive strength. We note that a significant proportion of bricks used in India do not pass the Indian Standard, making the strong alkali-activated bricks a more attractive alternative. Furthermore, through communication with brick makers in Uttar Pradesh that we have worked with to develop the alkali-activated bricks, we discovered that their methods for testing water absorption

are different than what we used. For similar brick mixes, our testing gave results that were several percentage points higher in water absorption than what was found in India—so it is possible that many more of the brick mixes tested in this thesis would satisfy Indian industry standards, and that our stringent testing methods penalized their performance.

Table 3: Compressive Strength of Common Bricks in Regions of India

Region	Compressive Strength (Mpa) (Sarangapani et al. 2002)	Compressive Strength (Mpa) (GSDMA 2005)
Andhra Pradesh	-	3 - 7
Assam	-	3.5
Bangalore	3 - 12	-
Chennai	2 - 15	-
Delhi and Punjab	7 - 10	7 - 15
Gujarat	3 - 10	3 - 10
Kanpur	14.6 - 23.7	-
Kerala	7.6 - 14.2	-
Madhya Pradesh	3.5 - 10	3.5 - 5
Maharashtra	-	5
Mumbai	4 - 7.5	-
Mysore	4 - 6.5	-
Pondicherry	5 - 11	-
Rajasthan	-	3
Uttar Pradesh	22.2	10 - 25
West Bengal	-	10 - 25

4.3 Further Research

Although this research was successful in producing an alkali-activated brick that is less environmentally burdensome than incumbent building materials while passing structural code, the mix design could be improved on several fronts: robustness, cost, and impact.

The sodium hydroxide solution is a dominating factor in price and impact, and lowering the molarity would directly reduce these elements. Previous research^{7,13,20} used a 2.0 molar and a 1.0 molar solution, and so although this thesis has been following the trend of lowering impact and cost on these fronts without sacrificing strength, this could possibly be reduced even further. Our lab has experiments in the pipeline to test 0.25 molar and 0.10 molar solutions.

Mixes I, J, and K exhibited that reducing ash content decreases water absorption without sacrificing too much strength. This experiment could be extended to determine at what point there is not enough silica extracted to form a sufficient amount of C-S-H, the microstructural binder matrix of the bricks. If aggregate wastes are found to provide a significant amount of extractable silica, this could further justify reducing ash content.

Tobermoritic C-S-H phases typically have calcium-to-silica ratios of 0.67 to 0.83, and based on data from inductively coupled plasma - optical emission spectrometry testing and X-ray fluorescence analyses, all of the mixes (except mix C, which uses Texas rice husk ash) are above this range. Table 4 displays the theoretical calcium to silica ratios in the design mixes. This implies that there is excess calcium available, and that silica could be the bottleneck in C-S-H formation. Because C-S-H fills pores thereby reducing water absorption, maximizing C-S-H content is key to a viable brick—however, the source of silica—biomass ash—is also very porous. Introducing more ash could increase silica and C-S-H content, but also increase void space. Further studies could be done to optimize the calcium-to-silica ratio, which is to say the ash-to-lime and C-S-H-to-porosity ratios as well. Three potential methods to increase silica extraction without increasing pore space would be to increase curing time, increase sodium hydroxide concentration, or introduce an aggregate precursor

material that contains available silica.

Calcium : Silica Molar Ratios for AA Brick Mixes								
	Ash	Lime	Aggregate	NaOH	L/S	Additive	Compaction	Ca:Si
A	50 SDBL	10	40 steel slag	0.5 M	0.28	-	35 Mpa	0.90
B	50 SDBL	10	40 clay	0.5 M	0.28	-	35 Mpa	0.90
C	50 TEX	10	40 clay	0.5 M	0.28	-	35 Mpa	0.78
D	50 SLVT	10	40 clay	0.5 M	0.28	-	35 Mpa	0.97
E	50 SDBL	10	40 clay	0.5 M	0.28	Silres (0.23%)	35 Mpa	0.90
F	50 SLVT	10	40 clay	0.5 M	0.28	Silres (0.23%)	35 Mpa	0.97
G	50 SLVT CR	10	40 clay	0.5 M	0.28	Silres (0.23%)	35 Mpa	0.97
H	50 SLVT CR	10	40 clay	0.5 M	0.28	-	35 Mpa	0.97
I	50 SDBL	10	40 calcined clay	0.5 M	0.28	-	35 Mpa	0.90
J	40 SDBL	10	50 calcined clay	0.5 M	0.28	-	35 Mpa	1.13
K	30 SDBL	10	60 calcined clay	0.5 M	0.28	-	35 Mpa	1.51
L	30 SDBL	10	60 steel slag	0.5 M	0.28	-	35 Mpa	1.51
M	40 SDBL	10	50 clay	0.5 M	0.28	Silres (0.23%)	35 Mpa	1.13
N	50 SDBL CR	10	40 clay	0.5 M	0.28	Silres (0.23%)	35 Mpa	0.90
O	50 SDBL CR	10	40 clay	0.5 M	0.28	-	35 Mpa	0.90

Table 4: Calcium to silica ratios in mix designs

There are still untested avenues that could reduce water absorption without the need for additives or carbon reduction. Although these methods were shown to be effective, they drive up cost and environmental impact. Compressing the bricks beyond 35 Mpa is one proposed method, as this could reduce pore space, but there is a practical constraint: many manual presses in India have an upper limit around 35 Mpa.¹⁸ Mechanical activation via

grinding could provide dual purposes of increasing reactivity due to increased particle surface area¹² as well as reducing pore space and water absorption. Inclusion of large, non-porous aggregate such as crystalline slags could also reduce absorption by reducing overall pore space.

Methods of implementation also need to be addressed. Although several contacts on the ground in India have helped to navigate this space, government building codes may still pose a significant hurdle even if the alkali-activated bricks pass all specifications as they are a novel material that has not yet been tested at industrial levels. Large-scale in-field testing could increase confidence in this area—perhaps starting with areas that are not as catastrophic if failure does occur such as sidewalks and residential buildings rather than multistory commercial buildings or bridges.

4.3.1 Material Substitution

Many potential aggregates exist as industrial wastes. Other steel slags, crushed brick (which calcined clay was used in this experiment to replicate), crushed concrete, aluminum dross, and shredded plastics are just a few. All of these are landfilled or illegally disposed of in India on huge scales, so their availability could further enhance robustness and perhaps brick performance.

An essential element in the formation of calcium silicate hydrate is calcium, which is currently provided solely by the 10% lime that is present in all mixes. Although lime is very effective in providing extractable calcium, it is also a dominating factor in price and environmental impact along with sodium hydroxide. Continuing the search for a waste material that supplies sufficient calcium could yield marked advancements in cost and impact.

Part II

The Economics of Ecosystem Services

5 Introduction

Natural ecosystems provide local, national, and global benefits in the form of ecosystem services and natural capital. Stocks of natural capital—plants, animals, water, soil, and minerals are all examples—can be harvested for liquidity or left undisturbed to provide a constant flow of ecosystem services. Ecosystem services are benefits to humans derived from functioning natural ecosystems, such as air purification, flood prevention, and climate regulation. As these services are not market goods, their loss due to material extraction is a negative externality⁴⁰ that is typically not considered in decision making. Ecosystem services are both vital and valuable because to mechanically replace them is generally very costly, whereas we receive their benefits for free from the natural environment. Examples include mangroves versus installing a seawall, natural water filtration versus a water filtration plant, natural carbon sequestration versus sequestering through technology, and pollination via insects versus costly mechanical pollination. Valuation estimates of the world's ecosystem services are on the order of \$125 trillion per year.⁴¹⁻⁴³

As important as ecosystem services are to our economy and health, they are not a market good and are generally considered to have zero intrinsic monetary value. This creates the illusion that because the price of ecological functions is zero, so is their economic value. The lands that provide these benefits are also habitually subjected to urbanization, conversion to agricultural land, deforestation, and mining without any compensation for the lost services. Recent studies state that more than 75% of terrestrial ecosystems globally are substantially degraded,⁴⁴ and have lost capacity to provide their natural services. Another recent study⁴³ indicates that 65% of ecosystem services are in decline, with 21% declining strongly. One

way to curb this environmental degradation and lessen the burden on mechanical systems to replicate what had been provided naturally is to recognize the monetary value we receive from intact ecosystems. Effecting policies that acknowledge their worth and mandate compensation could account for negative externalities, correct a market failure, and further incentivize use of recycled materials.

Although placing a tangible dollar value on ecosystem services is difficult and results in a large margin of error, there are several methods that produce estimates based on observed or predicted costs associated with ecological degradation. The majority of methods investigate the amount of money it would take to replace an ecosystem service with a man-made equivalent, or calculate the costs that would accrue if replacement projects are not undertaken. Examples include water retention of soil versus a stormwater drainage system, pollinators dying off and decreasing crop yield, health hazards from losing air purification, and mangroves or other coastal vegetation versus a seawall for flood and storm protection. Numerous studies have approximated ecosystem service values, many of which are compiled by The Economics of Ecosystems & Biodiversity (TEEB). Values from the TEEB Valuation Database⁴⁵ will later be attributed to services and used in calculations to estimate the worth of Indian tropical forest.

5.1 Incorporating Ecosystem Services into LCAs

Several frameworks have proposed incorporating ecosystem services into life-cycle assessments,^{40,46-57} and while these have spurred growth and attention in this field, no standard approach has yet prevailed. Review of literature indicates that almost all conventional life-cycle assessment methods ignore ecosystem services (with the exception of carbon storage).

Some research provides insight into how current methods account for human demand on ecological systems, but do not consider an ecosystem's capacity to supply services.^{40,46,47} This may create the illusion that a product is sustainable in comparison to other products, but its ecological demand is greater than the supply and still drives degradation of

environmental services.

Others argue to include ecosystem services in the life-cycle impact assessment methodology.⁴⁸⁻⁵¹ An advantage to this approach is that it streamlines inclusion of ecosystem services into life-cycle assessments, but a disadvantage is that values are not spatially-explicit as the impact assessment methods are generalized.

There are also a few studies that have proposed incorporating monetary valuation of ecosystem services in life-cycle assessments.^{40,50,52} Similar to the costing methods mentioned above, some of these rely on the change of ecosystem service provision as their main monetary indicator. In this study we rely on similar methods, and the advantages and disadvantages to assigning monetary values to ecosystem services are discussed below.

5.2 Direct Market Valuation

This thesis will tackle the problem from the vantage of direct market value. From valuations derived from the above or similar costing methods, tangible monetary values can be embodied in materials and other products to account for the ecosystem services that are lost during their production. Advantages to this approach are that it could streamline the process to impacting policy as it provides a uniform metric across all ecosystem services and products. For policy makers unacquainted with ecosystem services, implementing their value into land use decisions can be completely off their radar. Even for those who realize their importance and wish to include ecosystem service values in planning, the complexity and cost of conducting unique ecological analyses can become too big of a barrier. By adopting a simpler approach of infusing baseline, conservative ecosystem service values into materials (or the land they are extracted from), broader policy makers could include their value in strategies, planning, and laws. Even if the initial values introduced to policy are much lower than the true value we receive from ecosystems, this broad recognition could significantly add to the momentum of acknowledging environmental services. Such conservative, baseline values could be determined from previous studies included in the TEEB Valuation

Database or other reputable source—once accounting for biome type and location, the most relevant values available could be reduced to what decision makers feel comfortable to start with. Even very conservative values would be more accurate than the currently recognized ecological value of zero. As more scientific studies are conducted, the available values from databases will become both more refined and more geographically inclusive.

A main disadvantage of a monetary metric is an increased margin of error, especially because ecosystem service values are spatially-explicit and available valuations are currently geographically sparse. Indeed, not enough Indian-based studies were found to fully conduct this assessment, so this thesis draws upon conservative estimates from other regions to fill information voids. The Uncertainty & Imprecision section covers this topic more in depth.

This section aims to conduct a rigorous life-cycle assessment of alkali-activated masonry bricks and compare their environmental impact against that of incumbent building materials such as fired clay bricks, and express the importance of including ecosystem services as a metric in determining the lifetime impact of a product. The conventional assessment includes an evaluation of resource consumption, energy usage, and other environmental aspects associated with the production and use of the proposed alkali-activated bricks. In concert with the conventional LCA, there is motivation to show the embodied lost ecosystem services in these materials. This explicitly accounts for some of the hidden costs of raw material extraction and could provide further incentive to promote and utilize recycled materials.

6 Methods

6.1 Scope & Boundaries

The materials, processes, and products considered in this life-cycle assessment are listed here to set limits on this thesis's scope. The precursor materials used to create the alkali-activated bricks are Indian biomass ash, Indo-Gangetic clay, and hydrated lime. When combined with aqueous sodium hydroxide solution and set to cure at near-ambient temper-

ature, a binder is formed with characterizations of calcium silicate hydrate (C-S-H).

This thesis serves as a case study revolving around northern India. The biomass ash used in this study was obtained from the city of Muzaffarnagar, in the Indian region of Uttar Pradesh, and this will be reflected in the inventory and impact analyses.

The temporal boundaries of this study are bound between the obtainment of materials, whether through raw materials extraction or acquisition via industrial waste streams, and the implementation in construction. The long-term behavior and lifespan of the alkali-activated bricks is assumed to be similar to fired clay bricks for the purposes of this assessment.

This study pertains to only the direct and conventional uses of the bricks—materials acquisition, processing, and manufacturing. Although incineration of biomass such as rice husk and sugar bagasse to produce electricity certainly has environmental implications, this study only accounts for the use of biomass ash as if it were an unprocessed, raw material. Other industrial wastes that are discussed reside within the same assumption. End-of-life aspects are not included.

6.2 Design Mixes

Two design mixes of alkali-activated bricks will be included in this assessment, whose properties are shown in Table 5. Their contents, performance, and environmental impact vary enough to incite tradeoff consideration of mix design choice based on situational need. Biomass ash is the main precursor component in both mixes, and provides the silica and aluminum that, after extraction via alkali activation, contributes to the formation of calcium silicate hydrate (C-S-H) or calcium alumina silicate hydrate (C-A-S-H) binder. These cementitious binder matrices provide the structural strength of the material, making them useful in masonry construction.

Both mixes contain ten percent hydrated lime to provide enough calcium to form binder, and differing amounts of clay that, while initially thought would contribute to a binder matrix, did not supply much useful extracted elements and ended up acting as a low-

water-absorption filler material—useful in its own right as the biomass ash has relatively high water absorption. Both mixes also used a 1.0 molar sodium hydroxide solution to serve as the alkali-activating agent.

To provide context, a life-cycle assessment and ecosystem services analysis is also conducted on the traditional fired clay brick. Although fired clay bricks are the obvious incumbent material that the alkali-activated bricks could serve as replacements for and will be the only conventional construction material quantitatively assessed, the proposed binder could also potentially be pressed into precast sidewalk panels or other situations where low strength concrete is frequently used.

To determine a functional unit for this study, one must consider the fundamental service the bricks provide: structural support and volume of wall, sidewalk, or other structure. In most scenarios, once above a given design threshold dictated by building code, further strength does not provide additional benefit. For this reason, volume of masonry product will set the reference flow.

Table 5: Mix Designs

Properties	High ash content (HAC)	Low ash content (LAC)
Biomass Ash	70%	50%
Indian Clay	20%	40%
Hydrated Lime	10%	10%
Liquid-to-solid Ratio	0.40	0.28
Chemical Activator	1M NaOH	1M NaOH
Compaction Pressure	10 Mpa	20 Mpa
Curing Temperature	30°C	30°C
Water Absorption	38.0%	27.3%
Compressive Strength	10.5 Mpa	22.9 Mpa

6.3 Inventory Analysis

An inventory analysis is conducted to establish the relevant material and energy inflows into the alkali-activated bricks, and any releases of chemicals into the environment that may occur through precursor material obtainment, processing, manufacturing, or throughout their lifetime serving as structural masonry. The inventory used in the openLCA life-cycle assessment was constructed using the ecoinvent 3 database.⁵⁸

Significant flows of material and energy are categorized and quantified here for use in the life-cycle assessment. They will then be normalized to accurately compare the flows to each other and determine relative magnitudes of impact.

6.3.1 Materials

The materials used to create the alkali activated bricks are local clay, hydrated lime, biomass ash, sodium hydroxide solution, and tap water. The environmental impact associated with the extraction, processing, and other upstream impacts of these materials is derived from the ecoinvent 3.4 database.⁵⁸

The cumulative energy demand for the production of alkali activated bricks consists of the energy required to extract raw clay and lime, to transport raw clay and lime and biomass ash from their respective sites to the manufacturing facility, and the energy used to compact the bricks. Because the clay and biomass ash are sourced locally, it is assumed these materials are transported approximately 50 kilometers via unspecified trucks. Similarly, the lime was assumed to be transported 100 km, and the sodium hydroxide 200 km via trucks. The tap water is assumed to be available on site. There is also a small amount of electricity used in the compaction process, assumed to be 0.0025 kWh per brick for the mix compacted to 10 Mpa and 0.005 kWh per brick for the mix compacted to 20 Mpa.

Releases to the environment associated with brick development and use include carbon dioxide and possible seepage of alkali solution through leaching over time. The total global warming potential consists of carbon dioxide released from extraction and transport

of materials.

It should also be noted that most of the boiler ash is currently being landfilled or illegally disposed of in fields or farmland. When not properly disposed of, fine ash particles can be hazardous to human health. Although this factor is not included in the life-cycle assessment, streaming this biomass ash into bricks and away from landfills and other sites negates a current negative flow to the environment.

6.3.2 Selected Ecosystem Services

Although ecological systems provide dozens of benefits to humans, this study focuses on just five: erosion prevention, pollination, water purification, climate regulation, and carbon sequestration and storage. To be clear, these services are provided by an intact ecosystem as a whole—not the clay in particular, although the clay is integral to an ecosystem performing at its full capacity. Much of the value arises from vegetation, or potential vegetation, above the clay bed which is removed along with topsoil during extraction. Clay extraction and the associated top soil depletion and vegetation removal significantly affects an ecosystem's capacity to perform these functions.

The environmental services lost per the use of lime in the alkali-activated bricks (10% by weight) is not considered in this assessment, mainly to simplify the comparison to fired clay bricks by considering only the same material, clay, in each product.

Ecosystem services have spatially-explicit values, both because of regional biome classification and local societal needs. In this analysis, the value lost via clay extraction will be calculated for the region of Uttar Pradesh. This region in northern India is generally classified as tropical forest,⁵⁹ and so values derived from The Economics of Ecosystems & Biodiversity database are all of this biome type.

Because ecosystem service valuation is a relatively new concept and values are difficult to ascertain, studies and accompanying values are sparse. Table 6 presents the values chosen from the TEEB database, not all of which are India-specific due to data paucity. As is

elucidated in the following Uncertainty & Imprecision section, this study does not claim precision or relevancy of values used—its purpose is to present a possible framework and associated methods of capturing lost ecosystem service values in material production that could be streamlined into policy.

Table 6: Assessed Ecosystem Services

Ecosystem Service	Biome	Location	Value
Erosion Prevention	Tropical Forest	India	\$84 /ha/yr ^{45,60}
Pollination	Tropical Forest	Indonesia	\$46 /ha/yr ^{45,61}
Water Purification	Tropical Forest	World	\$433 /ha/yr ^{45,62}
Climate Regulation	Tropical Forest	India	\$9 /ha/yr ^{45,63}
Carbon Sequestration	Tropical Forest	World	\$2830 /ha ^{45,64}
Total:			\$571 /ha/yr + \$2830 /ha

Using the values from Table 6, the net present value of one hectare of Indian tropical forest can be calculated once a discount rate is established (a discount rate of 5% is used in this assessment). Use of discount rates in environmental evaluations are necessary to keep land values from becoming infinite—looking at Table 6, it can be observed that if a hectare of land provides \$571 per year indefinitely, its net present value is priceless. The net present value (NPV) can then be calculated using this discount rate (i), the total Annual Ecosystem Service Benefit (AESB), and the present carbon sequestration and storage value:

$$NPV = \int_{t=0}^{\infty} (1 + i)^{-t} * AESB dt + \$2,830$$

which leads to a net present value of \$14,500 for one hectare of Indian tropical forest due solely to the ecosystem services it provides at its full capacity. This does not include real estate value, natural capital such as timber or minerals, or agricultural potential.

6.4 Uncertainty & Imprecision

This thesis claims no precision of values—its objective is instead to present a case study for a possible framework to account for ecosystem services that are lost in the production of materials. Environmental service values vary by location, and so the values used in this study can do no more than act as approximates of the true, unknowable value. It makes intuitive sense to assess many benefits we receive from the natural environment qualitatively, and so to force a quantitative fiscal metric to these can be a bit convoluted and tortuous. In addition, the proposed method of using values from previous studies of similar biome type and, if possible, location introduces more uncertainty, but there are advantages as well. By using readily available values from the TEEB database or other reliable sources, one can place approximate values to the ecological and economic burden of a decision without performing a unique analysis. This could significantly streamline implementation of ecosystem services values into widespread policies. Because this method introduces so much uncertainty and error, initial policies could adopt conservative, baseline ecosystem service values, and supplementary spatially-explicit values could be added later if unique studies were performed.

7 Results

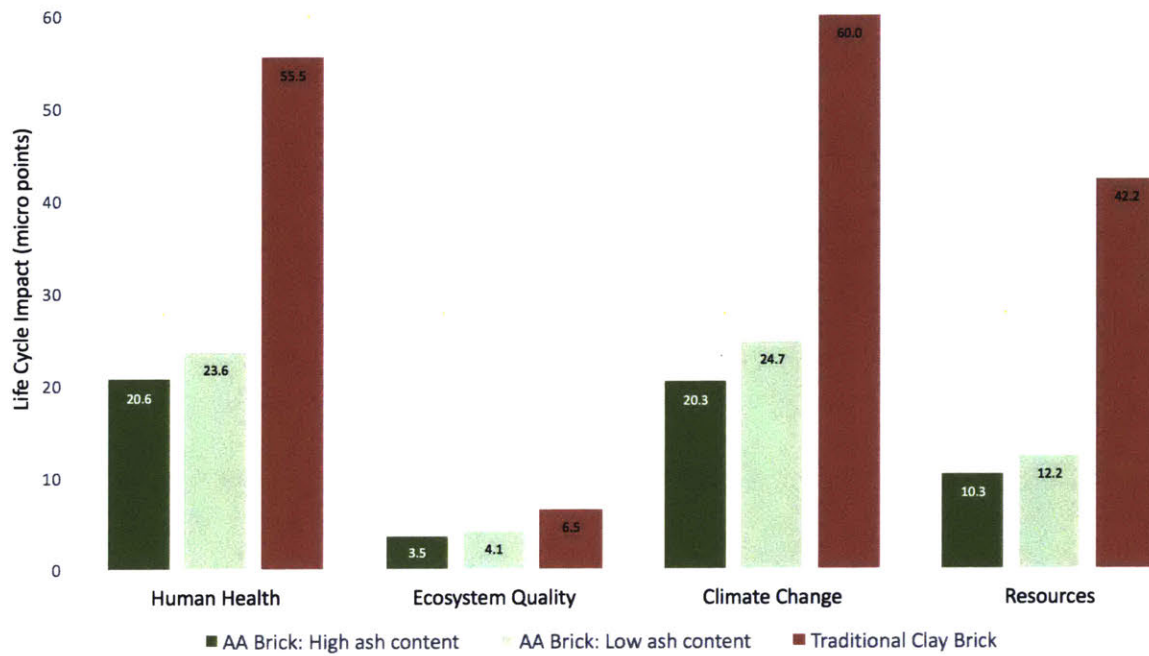
The life cycle impact assessment was conducted using openLCA 1.7 software, developed by GreenDelta.⁵⁸ All inventory materials and their associated upstream impacts were derived from the ecoinvent 3.4 cut-off database, and the analysis was done using IMPACT 2002+ (Endpoint) methods. Processes were represented as unit processes rather than system processes, and providers were chosen to be a general rest of world (RoW) source, as Indian-specific precursor materials were not available. Another important assumption was that because biomass ash is currently a waste product that is landfilled, it was categorized as an elementary flow with no associated upstream impacts.

The results from the life cycle assessment will be relayed first, and then expanded upon by inclusion of an ecosystem services analysis. The four typical categories associated with a life cycle assessment of a material, human health, ecosystem quality, climate change, and resources are analyzed in the first portion, with a fifth category of ecosystem services proposed and presented in the following section.

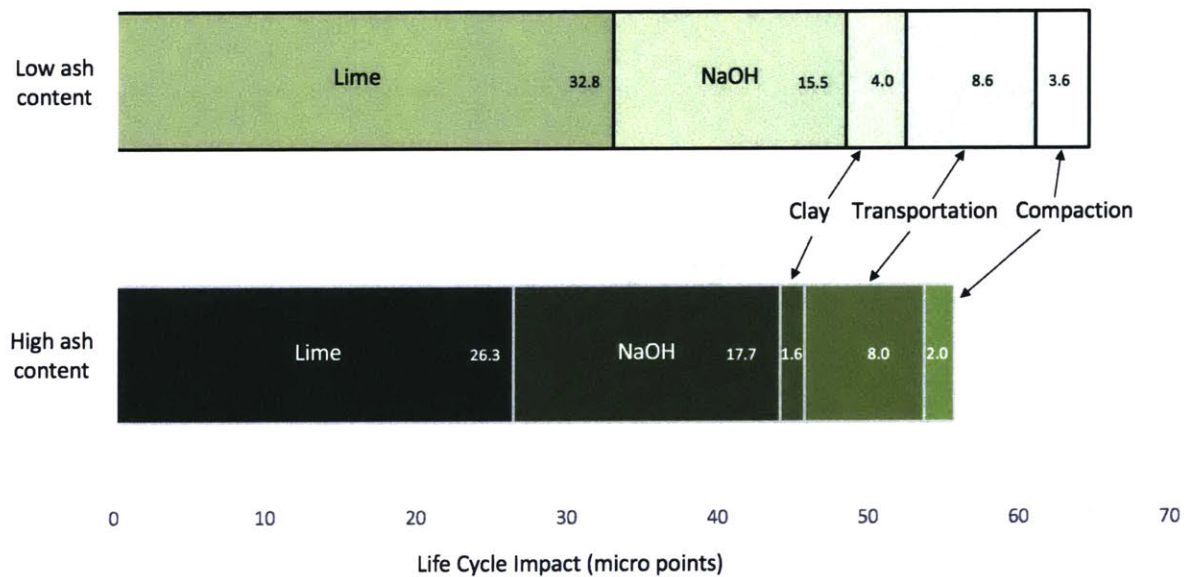
7.1 LCA Results

Figure 6a shows the normalized environmental impact across four categories for both alkali-activated brick mixes and a traditional fired clay brick. All impacts are presented in micro points per full-sized brick. Impact of alkali-activated bricks is significantly lower in all categories, particularly human health, climate change, and resources. Between the two mix designs, the high ash content (HAC) had roughly 10-20% lower impact across all categories compared to the low ash content mix (LAC). Both ash-based bricks had a quarter to a third of the impact that fired clay bricks had in human health, climate change and resources, and just over half the impact of fired clay bricks in the ecosystem quality category of the conventional LCA.

Among the alkali-activated brick designs, Figure 6b presents the role of different brick system constituents in determining impact. The largest contributor to environmental burden is the hydrated lime—10% in both mixes, although both because the LAC brick is denser and has a lower liquid-to-solid ratio, it contains more lime and therefore its impact is higher. The other major contributor is the sodium hydroxide solution, with transportation, compaction (electricity), and clay together accounting for less a fifth of the total impact. The environmental impact of clay is underestimated in this traditional life-cycle assessment, and will be expanded upon in detail in the ecosystem services analysis in the next section.



(a) Life-cycle impact of alkali-activated & traditional clay bricks according to IMPACT 2002+ (End-point) impact assessment methods



(b) Contribution of inflows to alkali-activated brick life-cycle impact

Figure 6

7.2 Ecosystem Service Valuation Results

To determine the value of ecosystem services that are lost when resources are extracted from undisturbed land, both the location and local human needs should be considered. The price of benefits derived from functioning ecosystems is spatially explicit with respect to both the land’s biome classification and proximity to human communities. Many services, such as water filtration and pollination, are significantly more valuable to humans when the ecosystem is near human populations and agriculture, respectively. Others, such as climate regulation and carbon sequestration, perform at a regional or global level and their values are more universal.

From an arbitrary hectare of northern Indian land, after assuming a half meter of overburden of organics and a clay bed depth of one meter,⁶ the amount of clay extracted per hectare can be calculated based on the net present value calculated earlier. This can easily be translated into the number of bricks available from one hectare, and, once the net present value is divided by this, we arrive at the value of ecosystem services lost per brick. This value for the traditional clay brick and both alkali-activated brick designs are shown in Table 7, and Figure 7 also displays these results with the price per brick broken down into individual cost of ecosystem services embodied in a brick. The results show that the traditional fired clay brick negates three times as much ecosystem service value as the low-ash content brick, and over seven times more than the high-ash brick. Between the two alkali-activated bricks, the higher clay content and higher density of the LAC brick led it to negate two and a half times more ecosystem service value than the HAC brick.

Table 7: Ecosystem Services Lost Per Brick

Brick Type	% Clay by wt.	Brick Mass	Ecosystem Services Lost
Alkali-activated, HAC	20%	1.60 kg	\$0.00043
Alkali-activated, LAC	40%	1.98 kg	\$0.00106
Traditional Clay Brick	100%	2.36 kg	\$0.00315

According to the Government of India Central Public Works Department,³⁰ the cost of a fired clay brick in northern India is about \$0.064 (4.5 INR), and so though the values in Table 7 are small, they are not insignificant. The results of this study indicate the cost of lost ecosystem services is approximately 5% the cost of a brick, and so if the embodied ecological value of the clay extraction was accounted for in the market price, bricks would be ~5% more expensive. On the massive scale that India’s population and construction boom is taking place, this could lead to an industry shift towards more sustainable materials.

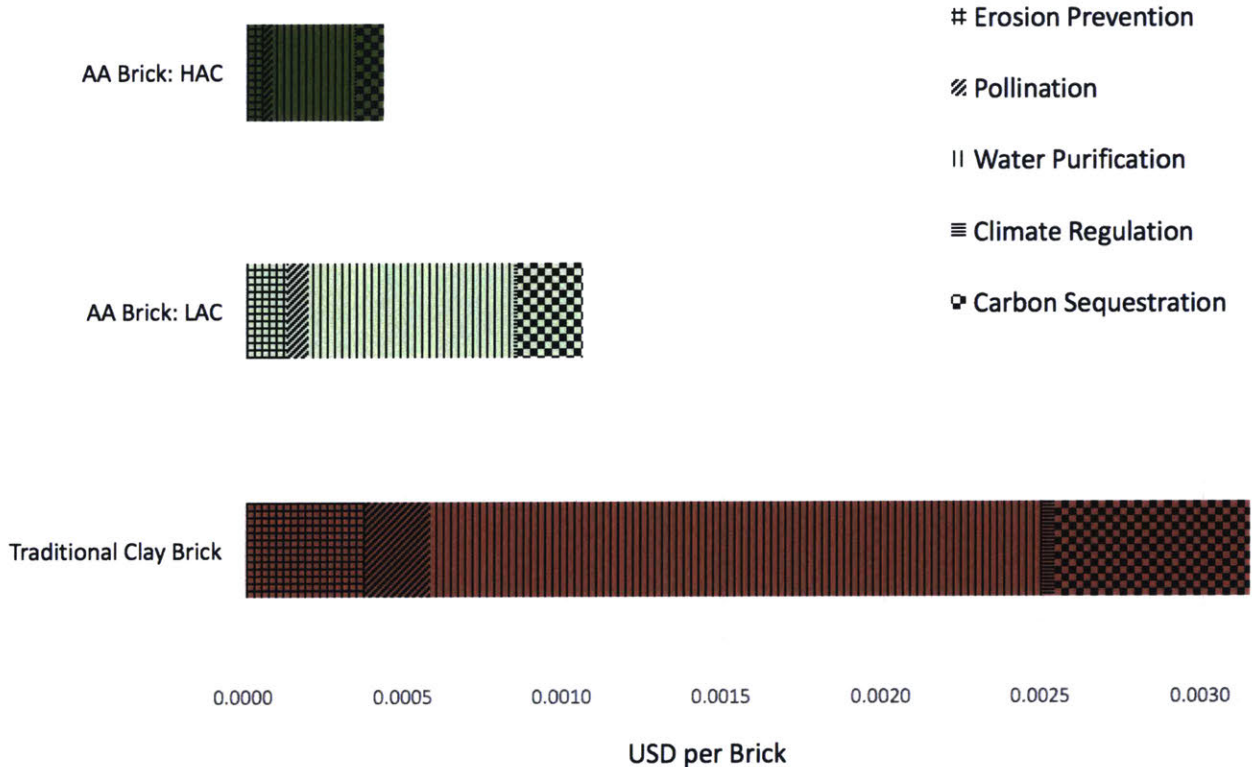


Figure 7: Value of ecosystem services lost per brick

Figure 8 shows the relative, normalized impacts of the alkali-activated bricks and traditional clay bricks across the conventional four environmental impact categories and ecosystem services. Human health, ecosystem quality, climate change, and resources are all in micro points and ecosystem services is measured in USD, and so while it’s appropriate to compare

masonry units within the ecosystem services category, there is no quantitative foundation to compare relative impacts between ecosystem services and other categories. Still, the figure shows that both alkali-activated brick designs are substantially lower than traditional clay bricks across all five categories.

The difference between the HAC and LAC mixes is significantly augmented with the addition of the ecosystem services category, as the HAC mix requires half the amount of clay to be extracted when compared to the LAC mix. Separation of impact from traditional clay bricks and alkali-activated bricks is further emphasized by realizing a more holistic burden that clay extraction places on the environment.

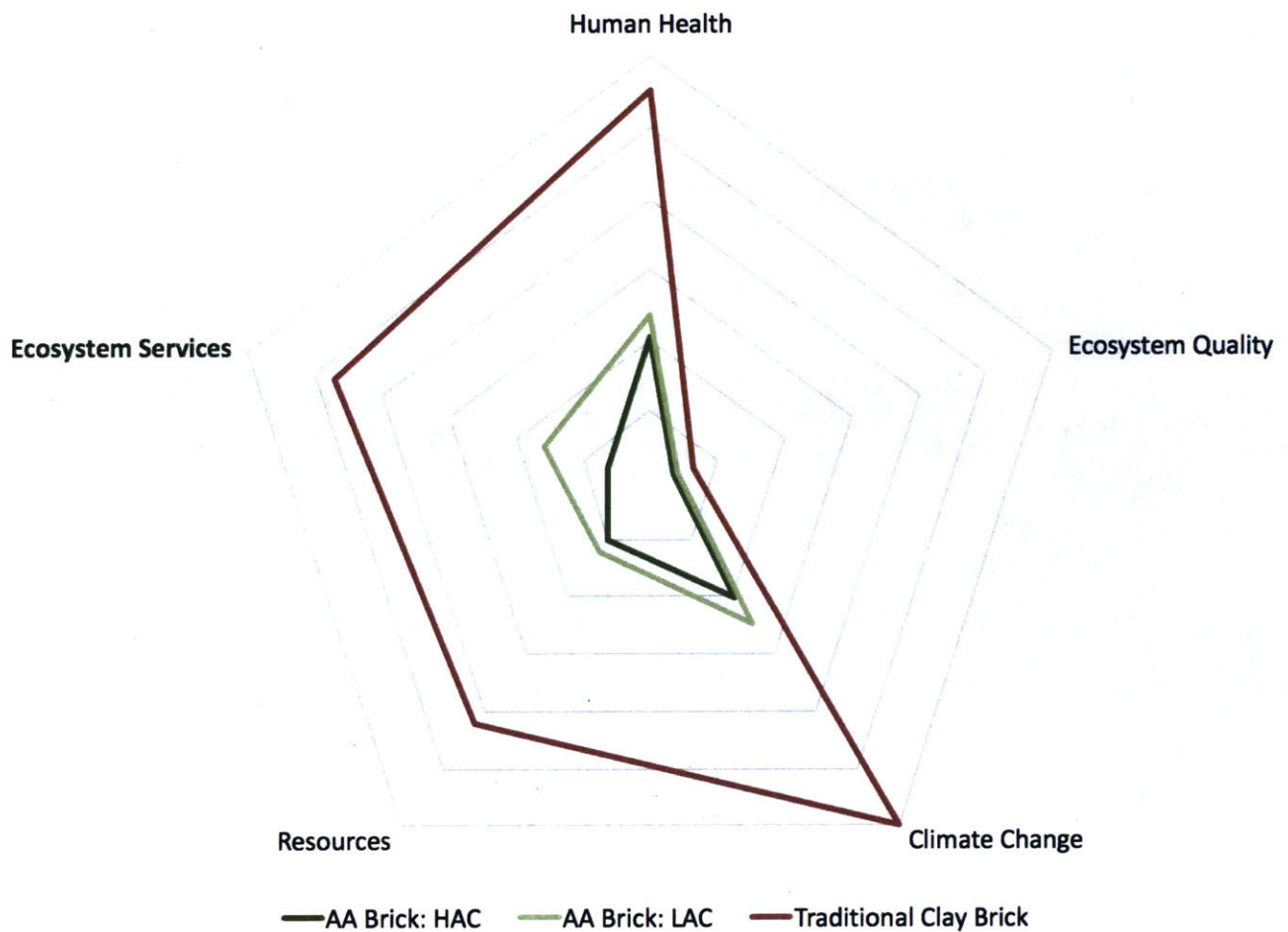


Figure 8: Environmental Impact of Alkali-Activated & Traditional Clay Bricks

8 Discussion

Although it was previously determined by Poinot et. al that alkali-activated bricks of similar mix designs have significantly lower environmental impact than traditional clay bricks, this analysis argues that lost ecosystem services due to clay extraction is a negative externality that is not captured in the market nor conventional life-cycle assessments, and alkali-activated bricks pose much less of an environmental burden than traditional clay bricks in this category. While the LAC mix has higher impacts across the board when compared to the HAC mix, it also has higher compressive strength (22.9 Mpa versus 10.5 Mpa) and lower water absorption (27.3% versus 38.0%)—and so desirability between the two may be situational.

The specific ecosystem service values used for this assessment are relevant but inaccurate. If this framework were proposed as novel policy, much more conservative values would be presented—perhaps less than 10% of what was used in this thesis—to minimize any skepticism or uncertainty of the legitimacy of ecosystem services while they are just entering the minds of many non-environmental policy makers. It is understandable that some might not accept even these conservative values, because in the complex science of ecological-societal interaction, it is very difficult to arrive at confident numbers. We should be confident, however, that the benefits we obtain from the natural environment does not equate to zero monetary value, and that in being vigilant not to overestimate, we are continuously and dangerously underestimating.

For example, the value of \$46 per hectare per year for pollination arises from a study conducted in Indonesia evaluating the economic return on coffee yield of farms different distances from pollinator hubs.⁶¹ The economic value of pollination wholly depends on the proximity of the land that provides habitat to pollinators to agricultural land—pollinators very far away from any farms provide humans with close to \$0, but if within the forage distance of pollinating insects, or even some bats or birds,⁴³ this value sharply rises. Pollination values in the TEEB Valuation Database range from \$6-\$400/ha/yr. If the true derived ben-

efit from pollination across Uttar Pradesh actually averaged to be only \$5/ha/yr, installing an overestimate of \$6/ha/yr into policy would still make a more efficient market than the current recognized value of \$0/ha/yr.

If this were extrapolated across many ecosystem services, land conversion might become a more expensive choice, and materials that are extracted from the land (clay bricks) could become more expensive while sustainable building materials (bricks derived from industrial waste) might be seen as a more attractive alternative.

The conventional life-cycle assessment portion of this thesis confirmed what we hypothesized—alkali-activated bricks derived from industrial waste have lower impacts on human health, ecosystem quality, climate change, and resources than traditional fired clay bricks. The ecosystem service valuation results revealed further separation between the two construction materials by looking at ecological impact, and offers a method to quantify this difference. For the market to efficiently drive consumer choice on this matter, it must reflect the true cost of the two materials to society.

8.1 Further Technology & Policy Research

Alkali-activated masonry systems continue to show promise as alternatives to traditional construction materials. Demand for building materials is dramatically increasing in India, and these bricks derived from biomass ash waste pose a sustainable solution. This study reinforced that alkali-activated bricks can have a lower environmental impact compared to traditional clay bricks via a life cycle assessment, and were also shown to pose a much lower ecological burden via an ecosystem services evaluation. Capturing the value of environmental services in the market by making their cost embodied in the price of materials may be an effective way to streamline their recognition into policy. This project to develop a sustainable, scalable, financially viable masonry brick derived from industrial waste streams has been developing over several years, and although progress has been made in the lab and the field, further research could yield marked advancements. Further investigations into ma-

terial substitution of brick ingredients and policy frameworks to incentivize use of sustainable masonry could make their in-field viability more robust.

8.1.1 Material Substitution

The main reason for inclusion of clay in the mix designs was to lower water absorption—biomass ash has relatively high absorption, and building codes mandate adherence to an absorption threshold.²⁸ However, the clay has not been reactive as the sodium hydroxide has failed to extract sufficient desirable phases to contribute to the binder matrix—essentially, the clay is currently serving as a low water absorption filler. Future research could focus on replacing this filler material with another industrial waste to cut down on environmental impact. Potential candidates include crushed brick, crushed concrete, steel slag, and aluminum dross. These are all either recycled or waste materials, and all with relatively high compressive strength which could serve as a coarse aggregate to supplement the cementitious binder’s strength.

The two largest contributors to environmental burden are the sodium hydroxide and hydrated lime. Further tests could be conducted to determine if the molarity of the sodium hydroxide solution could be lowered without sacrificing strength or durability, which would considerably lower the overall impact of the product. Replacing lime might be more difficult, as it is essentially the sole contributor of calcium (necessary for C-S-H and C-A-S-H binders), and no other industrial waste that has been tested by MIT’s Olivetti Group has yet provided sufficient calcium. More tests on a broader range of industrial waste streams could prove to be fruitful, though.

8.1.2 Environmental Metrics & Ecosystem Services

Accounting for ecosystem services in the market has been the subject of debate for decades, and while this thesis is not proposing an umbrella solution to capture the lost value, further research in this area could foster possible solutions. Including a metric of

embodied ecosystem service value in materials could spur broader recognition of the benefits lost to humans in materials' production, and perhaps a framework could arise to correct this market failure. The direct monetary valuation framework proposed in this thesis has its pros and cons, as discussed earlier, and whether or not this method is adopted by others, the takeaway is that approaches to account for ecosystem services should be both accessible to policy makers and technically appropriate.

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