PROJECT TITLE: Comprehensive feasibility assessment for use of rice ash in concrete

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OBJECTIVES AND EXPERIMENTS CONDUCTED, BY LOCATION, TO ACCOMPLISH OBJECTIVES:

The objectives of this work are outlined below:

Objective 1: Assess the effects of biomass preparation techniques used in rice-based energy production on the properties of RSA and RHA for use in concrete.

Objective 2: Determine the influence of rice-based ashes on the strength and the durability of concrete.

Objective 3: Perform life cycle assessments for different permutations of energy production from rice-waste and use of ash in concrete to determine their economic and environmental impacts.

The experiments and analysis to meet these objectives are outlined below:

Objective 1: Rice-based biomass was prepared by chopping straw to a similar gradation to rice hulls. Hulls and straw were either combusted with: (a) no further treatment; (b) additional leaching in tap water; or (c) additional leaching in an acid solution. Leachate was tested for soluble elements and ash produced was used in the production of mortar to examine effects on cement-based material properties. Note: at the date of this report, experiments are ongoing for oxide composition of ashes and for the effects on mortar properties using these ashes.

Objective 2: Using rice-ash from EnPower's bioenergy facility in Williams, CA, experiments were performed to test the effects of using rice-ash on: (i) compressive strength; (ii) flexural strength; (iii) shrinkage; (iv) alkali-silica reaction; (v) sulfate-induced dimensional instability; and (vi) chloride ingress in concrete. Note: at the date of this report, experiments are ongoing for sulfate-induced dimensional instability and chloride ingress in concrete.

Objective 3: To meet this objective, surveys were developed and administered either in-person, by phone, or by email to determine feasibility of different stages of rice biomass treatment, storage, and distribution. Data are being compiled from these sources and from the literature (including grey literature) to assess the economic and environmental impacts of using rice-based ashes in concrete.

All experiments and/or analyses done to accomplish these objectives were performed on the University of California, Davis campus, with the exception of some surveys, which were administered off-campus. To complete some of the proposed work, ash samples will be sent to an analytical facility off-campus to determine oxide composition in a timely manner.

SUMMARY OF 2019 RESEARCH (major accomplishments), BY OBJECTIVE:

Research is still underway, but to date, the following major accomplishments have been made by objective:

Objective 1: Ashes have been prepared from rice hulls and rice straw under each of the leaching conditions. Our results show that leaching rice biomass can remove 220 to 340 mg/L of potassium from rice hulls and 430 to 800 mg/L of potassium from rice straw, with what we anticipate to be the higher levels with straw due in part to the higher concentrations of potassium in straw compared with hull even if ash concentrations are lower. Acid leaching did not improve the removal rate of potassium from rice straw; although, in most cases, it did remove more soluble elements than water leaching.

Objective 2: Results indicate that while use of untreated rice hull ash from current energy-producing methods may lower compressive and flexural strength (approximately 15% loss of strength at 28-days), the effects on shrinkage and alkali-silica reaction are not substantial.

Objective 3: Data were compiled for an economic feasibility assessment from rice biomass acquisition up to use in concrete. Leveraging material property data and available modeling resources, economic and environmental impacts will be assessed.

PUBLICATIONS OR REPORTS:

A report will be compiled summarizing the work done and the findings from this research; an interim version of this report is being submitted with this document. It is also anticipated that at least one peer-reviewed publication will result from this research.

CONCISE GENERAL SUMMARY OF CURRENT YEAR′S RESULTS:

Findings to date suggest that there might be potential for rice-based ashes in concrete production. While hull leaching with the acid solution consistently removed higher levels of all soluble elements studied, for rice straw, the removal of K and Na were higher with tap water than with an acid solution. This finding suggests that the less expensive route of leaching (i.e., that without additional acid) could be a favorable means of recapturing minerals. Experimental findings of concrete mixtures showed the use of rice hull ash could contribute to some changes to compressive and flexural strength, but limited change in durability properties were noted. Finally, while rice straw is a larger potential commodity, there are additional logistical issues associated with collecting, storing, and utilizing the straw ash beyond those noted for rice hull ash, which will be factored into the economic and environmental assessments.

Comprehensive feasibility assessment for use of rice ash in concrete
Interim report

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1. Introduction

The availability of conventional mineral admixtures, such as fly ash and ground granulated blast furnace slag, that can be used in the production of concrete to meet performance and carbon emission reduction requirements is becoming severely constrained in certain regions [1]. A preliminary review of the literature has shown that rice-based ashes have a high potential to find a market in this resource-starved industry [2]. It has been shown that under proper combustion methods, rice hull ash (RHA) can contribute to desirable properties in concrete [3]. The use of rice-straw ash (RSA) is constrained by its chemical composition, including high potassium levels, which lead to undesirable properties in concrete. The interactions of current biomass preparation and combustion methods to improve bioenergy conversion on the properties of both types of ashes are not known well enough to begin using them in concrete.

The increasing demand for alternative supplementary cementitious materials (SCMs) coupled with the availability of rice ash materials could lead to these ashes being a desirable regional pozzolanic material. For example, due to its large and growing population, California is the second largest producer of cement in the United States [4]. Cement, which is used in the production of concrete and mortar, often requires mineral admixtures. The most popular mineral admixture in California is fly ash, a byproduct from coal combustion. Currently, to meet environmental impact and performance goals, California uses approximately 1 million tons of fly ash annually [5] (approximately equivalent to 15% of the mass of Portland cement produced in the state [6]). However, because California does not combust coal as a primary source of energy, it has to import all of the fly ash it uses from other states, increasing costs and environmental impacts. The nearest important sources of fly ash for California have been the Navajo coal power station in northeastern Arizona, which has been moving towards closing in 2019, and coal power stations in Wyoming facing issues of economic and environmental viability. By 2050, it is projected that cement demand in California will increase by 65% beyond 2015 levels [7, 8] and with it, demand for more SCMs. The potential availability of RHA and RSA (estimated to be approximately 400,000 tons annually in California based on [9-11]) and the demand for mineral admixtures is a strong motivator for expanding the understanding of use of rice-based ashes in concrete. There is potential for rice ash to be economically, logistically, and environmentally viable as an additive in concrete [12]. Research must verify the feasibility of this product for the concrete industry to accept it. While not as constrained in fly ash production as California, regions in India that are struggling with best management practices for rice residues [13] could benefit from a coupled avenue for recovery (as could other rice growing regions, such as China): the production of bioenergy and a supplementary cementitious material for an area with growing demand for both [14-16].

Experimental investigations will be conducted to determine the effects of rice-hull and rice-straw preparation and gasification temperatures on the characteristics of ashes produced. Initial studies have shown that biomass treatments, such as leaching in water, can lead to a reduction in alkali metals (particularly potassium) present in biomass and an associated reduction in agglomeration of glassy substances during their combustion [17-19]. Further, while the temperature for production of ash with desirable properties for use in concrete is quite low, the use of gasification methods has shown potential to produce ash at a low temperature with reasonable energy returns [20]. This work will investigate application of such methods on their ability to produce high quality ash.

Experimental investigations will be conducted to determine the effects of biomass-ash production methods on the properties of concrete. The literature has robust assessments of the use of rice-hull ash on concrete strength (e.g., [3, 21, 22]); however, the literature on the use of rice-straw ash and the durability properties of concrete using either ash are more limited.

In order for RHA and RSA to become accepted as an SCM and competitive in the market, there are several assessments of the properties of these materials in concrete that need to be carried out. It has been shown that in the production of reactive RHA, the combustion practice (e.g., controlled or uncontrolled combustion, combustion temperature, combustion technology) can play a large role in the properties of the resulting ash [10, 23, 24]. Beyond those parameters, treatments to the biomass prior to combustion that have been pursued to produce the bio-derived energy, such as leaching, can reduce the presence of alkali metals (e.g., potassium) [25], which could be beneficial for use of rice-based ash in concrete. However, the effects of such methods on RHA as a mineral admixture are limited and their effects on the viability of RSA as a mineral admixture in concrete are not present in the literature. Experimental assessment of the properties of rice-based ashes produced using such techniques and how their inclusion affects the properties of concrete must be undertaken.

The goal of this work is to investigate newer biomass treatment methods for bioenergy on the potential to produce viable rice-based ashes for use in cement-based materials as well as to quantify economic and environmental impacts of rice-based ashes. Specifically, experimental and analytical techniques are applied to elucidate the effects of leaching protocols and temperature of combustion on rice-based ash properties. Concrete mixtures formed with rice ash from current bioenergy production methods were examined to determine mechanical and durability properties. Further, data were compiled to quantify the economic feasibility of using rice-based ashes in concrete.

2. Materials and Preparation

2.1. Materials

For this work, rice hulls and rice straw were from Northern California suppliers. Rice hulls were donated by the Farmer’s Rice Cooperative in Sacramento, California and obtained on August 13th 2019.

Rice straw was acquired from Windmill Feed in Woodland, California on August 16^{th} 2019. Neither biomass resources underwent treatment prior to their collection for use other than the extraction of rice grains from the hulls or the removal and baling of straw materials from the field. After materials were collected and between preparation stages stipulated below, they were stored at ambient conditions indoors.

To examine the effects of using the rice-based ashes produced in cement-based materials, mortars were made. The Portland cement (PC) used in these mortars was ASTM Type II/V PC obtained from Lehigh Southwest Cement Co in Stockton, CA. The mortar batched for this work used natural sand as the fine aggregate (with a 99.95% passing rate through a #4 sieve). This natural sand was locally sourced from Esparto, California.

2.2. Grinding and Leaching of Biomass

While hulls were mechanically removed from the grains when milled, leaving remnant biomass at a relatively small size, straw was ground down to have a similar size distribution to facilitate leaching and combustion stages. To grind the rice straw, a hammermill was used with a 1-1/4" sized sieve to ensure straw particles were equivalent or smaller to this dimension.

Leaching of biomass was performed using two leaching solutions: (i) water; (ii) 0.5 M phosphoric acid (H_3PO_4) solution. These two leaching methods were selected due to their reported success at removing unwanted alkali metals from rice-based waste [25, 26]. Comparisons were drawn to biomass that was combusted without prior leaching, i.e., untreated (see Table 1).

For leaching in water, 15 L of water was used for every 1 kg of biomass. Water was mixed in with biomass in low-density polyethylene containers and agitated every 30 minutes for a total period of 5.5 hours. Afterwards, biomass was dewatered by manually compressing to remove excess moisture and oven dried at 100°C for 2 days. Moisture content readings were taken from non-leached biomass, leached biomass, and leached plus oven-dried biomass. Moisture content readings were taken by weighing samples and oven-drying samples until change in weight is less than 0.5% between readings at intervals of 24 hours or greater.

2.3. Biomass Combustion

To produce rice-ash, hulls and straw underwent a two stage combustion procedure. First, biomass was torrefied at 250°C for 40 minutes to remove volatile organic matter to avoid ignition and uncontrolled temperatures in sample processing at higher temperatures. Following torrefication, matter was brought to higher temperatures. Three temperatures were used to determine effects on ash product: 600°C, 850°C, and 1100°C (see Table 1). Each of these temperatures required different furnace times, namely, rice-based ash was prepared at 600°C for 8 hours, 850°C for 4 hours, or 1100°C for 1 hour, depending on the preselected furnace treatment.

Table 1. Rice hull and rice straw ash preparation matrix

Leaching Condition / Combustion Temperature	Untreated	Water Leaching	H_3PO_4 Leaching
600°C	Rice Hulls & Rice Straw	Rice Hulls & Rice Straw	Rice Hulls & Rice Straw
850°C	Rice Hulls & Rice Straw	Rice Hulls & Rice Straw	Rice Hulls & Rice Straw
1100°C	Rice Hulls & Rice Straw	Rice Hulls & Rice Straw	Rice Hulls & Rice Straw

2.4. Mixture Proportions and Mortar Batching

Concrete mixtures were made using two mixture proportions: one containing no rice ash and one containing 15% replacement of Portland cement by mass with rice ash obtained from the EnPower bioenergy facility in Williams, CA. Mixtures were batched using the same proportions of water, fine aggregates, and coarse aggregates. No chemical admixtures were used. Specimens were cast from these concrete mixtures to assess compressive strength, flexural strength, drying shrinkage, and alkali-silica reaction.

3. Experimental Methods

3.1. Concrete Compressive and Flexural Strength

Mechanical compression and flexure testing were conducted on mortar specimens after 28 days of curing. Compression tests were conducted on a SoilTest CT-950 load frame following ASTM C39 testing procedures [27]. Cylinder specimens were capped on either end with neoprene-padded aluminum cap and specimens were loaded under force control. Five specimens were tested for each mixture. Ultimate strength of the concrete mixtures was determined based on the maximum load reached before softening or failure occurred.

Flexural strength was determined by performing three-point bend tests after 28 days of curing. Experiments were performed on a MTS Testline Component load frame managed by an MTS TestStarIIs controller following ASTM C293 testing procedures [28]. Three specimens were tested from each mixture and ultimate strength was determined based on the maximum load reached prior to failure.

3.2. Concrete Drying Shrinkage and Alkali-silica Reaction

To determine the effects of partial replacement of cement or fine aggregates with rice ash on shrinkage and alkali-silica reactivity, mortar specimens were cast to have the same binder content and replacement ratios as the concrete mixtures tested. Drying shrinkage experiments were conducted following ASTM 596 testing procedures [29]. Specimens were removed from molds after 1 day of curing and placed in a conditioning chamber set at 25°C and 50% relative humidity. Alkali-silica reactivity experiments were conducted following ASTM C1567 testing procedures[30]. Three mortar prisms were cast for each mixture for both tests. The effects of time on length change of these specimens were measured at 0, 14, 21, and 28 days.

3.3. Leachate Chemical Analysis

To determine changes to solutions used in leaching of the straw and hulls, element composition of the leaching effluent and the pH were measured and compared to water prior to leaching. To collect leachate, the effluent remaining in the leaching tubs after dewatering were vigorously stirred for 15 seconds and then passed through a coarse sieve to remove large pieces of remaining biomass. Water prior to leaching was collected from the same tap as the water used in the water-leaching and the acid-leaching; water was collected from the faucet after running it for 30 minutes. Solutions were stored in polypropylene containers at 7°C until testing.

Readings were taken for soluble salts, K, Ca, Mg, and Na, as well as micronutrients, Zn, Mn, Fe, Cu, in the leachate. Concentration of these elements was quantitatively assessed through two primary means utilizing pressure digestion/dissolution of the solution. K, Na, Zn, Cu, Mn, and Fe concentrations were determined through atomic absorption spectrometry; Ca and Mg concentrations were determined through inductively coupled plasma atomic emission spectrometry. Soluble salt and micronutrient concentrations were measured by the University of California Analytical Chemistry Laboratory. The pH of solutions was tested using a ExtechSDL 100: pH/ORP/Temperature Datalogger pH meter with +/- 0.02 pH accuracy.

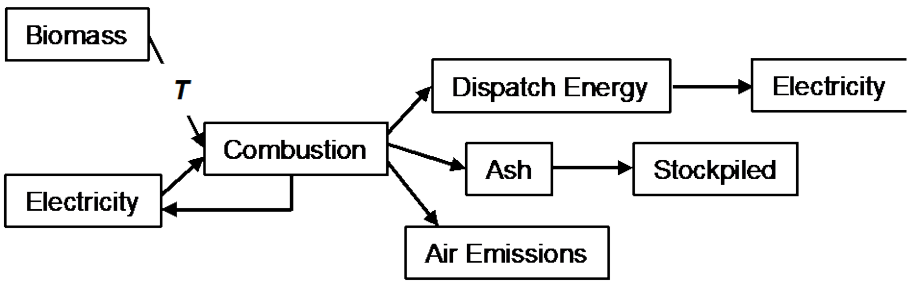
3.4. Surveys to Determine Economic Feasibility

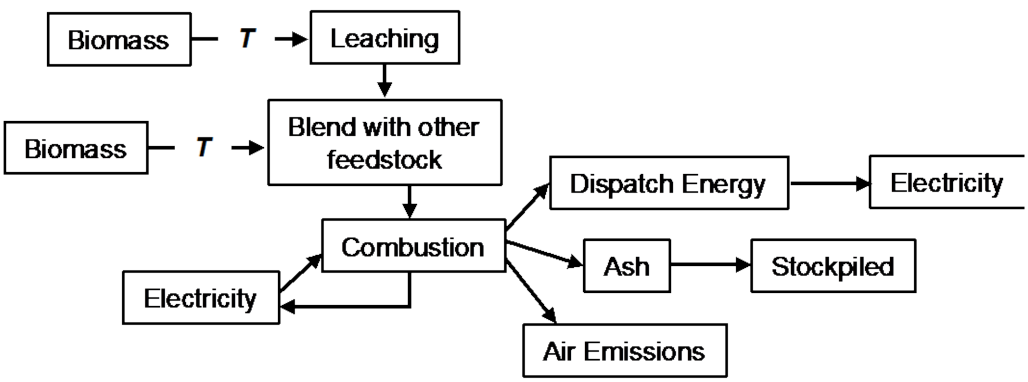
To determine benefits and constraints that could affect the economic feasibility of using rice-based ashes in concrete, as well as determine the potential for the leaching considered in this work, surveys were given to several industry representatives. These included representatives from bioenergy facilities (data collected through written survey feedback and phone interviews), hullers and hull management representatives (data collected through in-person interviews), straw balers (data collected through in-person interviews) and concrete suppliers (data collected through written survey feedback and in-person interviews).

The survey used to collect data is shown below in italic text. For the conversations in-person and on the phone, additional discussion beyond these foundational questions was sought when representatives were responsive.

Bioenergy:

- *What is the function relating operating temperature to energy output?*
- *What are the reasons for typical combustion temperatures, which are higher than optimal to produce supplementary cementitious materials? Is it solely for energy production efficiency or are there other reasons (e.g., reduction of air pollutants)?*
- *Can rice-based bioenergy plants be used as peaker plants?*
- *What do you anticipate the cost of biomass feedstock to be? Is it free? Are you paid to take it away? What are the costs of rice feedstock relative to competitive biomass feedstock? How do you anticipate those costs to vary in the next 10 years?*
- *How are you currently storing the ash produced from biomass combustion?*
- *What are the approximate electricity and energy inputs needed to operate the bioenergy facility? Are there any other inputs/outputs from the plant other than the biomass and energy?*
- *Does the flow chart for "business as usual" as we have depicted it seem correct or are there errors?*

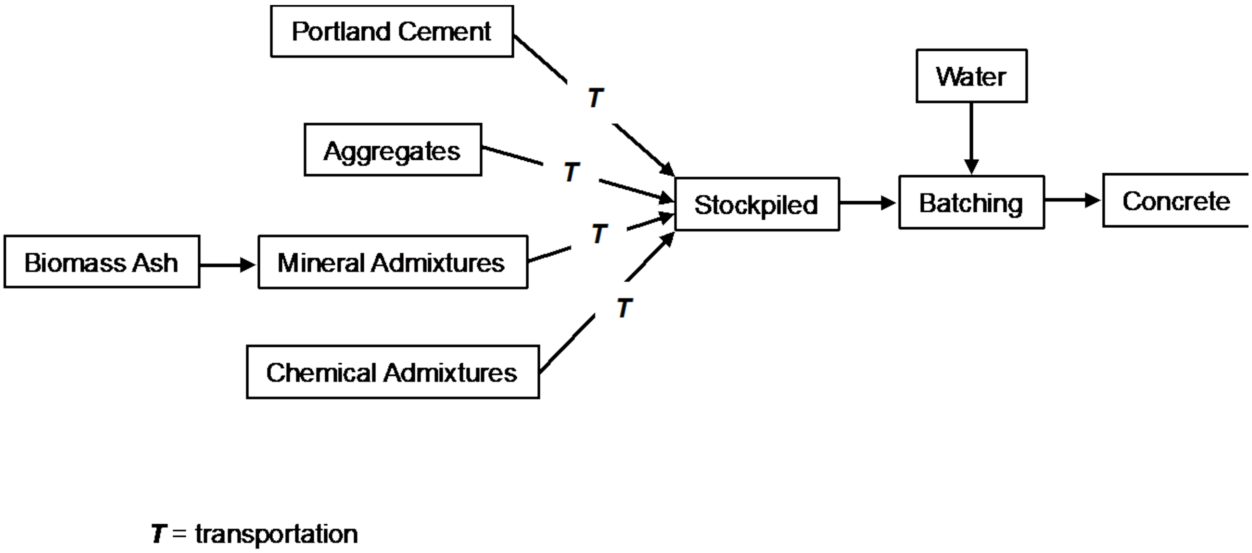




T = transportation

Concrete:

- *What do you see as the potential for rice-ashes to replace competitive pozzolans?*
- *How much are ready-mixed concrete producers willing to pay for pozzolans from rice?*
- *What is the demand for pozzolans and the current amount being paid to purchase pozzolans? How do you anticipate those costs to vary in the next 10 years?*
- *What is the seasonal demand for pozzolans?*
- *What are the pozzolan demands by region? (e.g., Northern California, Central California, Southern California)*
- *Does the flow chart for "business as usual" as we have depicted it seem correct or are there errors?*



Rice Mills, Hullers, and Straw Balers:

- *What is the cost of fertilizer that would be needed if straw was removed from the fields?*
- *Does the flow chart for "business as usual" as we have depicted it seem correct or are there errors?*
- *What is total potential supply?*
- *How many locations are straw and hull available at?*
- *How does hull and straw supply vary across the year, and from year to year?*
- *What are possibilities for processing of hull and ash at the mill or off-site?*
- *Any ideas of variability of hull and straw (mostly about the chemical components, but also water contents, other properties)*
- *What are competing uses and what are their approximate price points or costs of disposal?*
- *What are costs and equipment associated with cutting straw? Is baling necessary to transport straw? If so, what are the costs and equipment for baling?*
- *What is a leaching process that you are currently implementing? Would leaching ever occur in the field or would it occur at a second location?*
- *What are the logistics in preparing rice biomass? When would it be done by a farmer? Middle person (most likely, as farmers and energy plants won't want to deal with it)? Energy plant?*

4. Results

4.1. Concrete Compressive and Flexural Strength

A 15% replacement of cement with rice hull ash acquired from conventional bioenergy production methods resulted in a moderate change to 28-day compressive and flexural strength (see Figure 1). Namely, approximately a 15% reduction in strength was noted for both cases. While a reduction in strength is not necessarily desirable, it must be noted that this 15% reduction is less than the reduction in strength that would have been found from removal of 15% of cement with no replacement and, depending on proportions used, can exceed strength of a 15% fly ash replacement mixture [31]. The likely reason for these shifts in properties is that the rice ash could be acting as a pozzolan that could contribute to later-age strength, but less so to early strength. With grinding, rice hull ash has been shown to become more reactive [10], so if early age strength was desirable, post-combustion processing may contribute to desirably properties. Further, the ability of rice hull ash to behave similar to or better than fly ash in concrete is critical, as the use of fly ash is well established in practice.

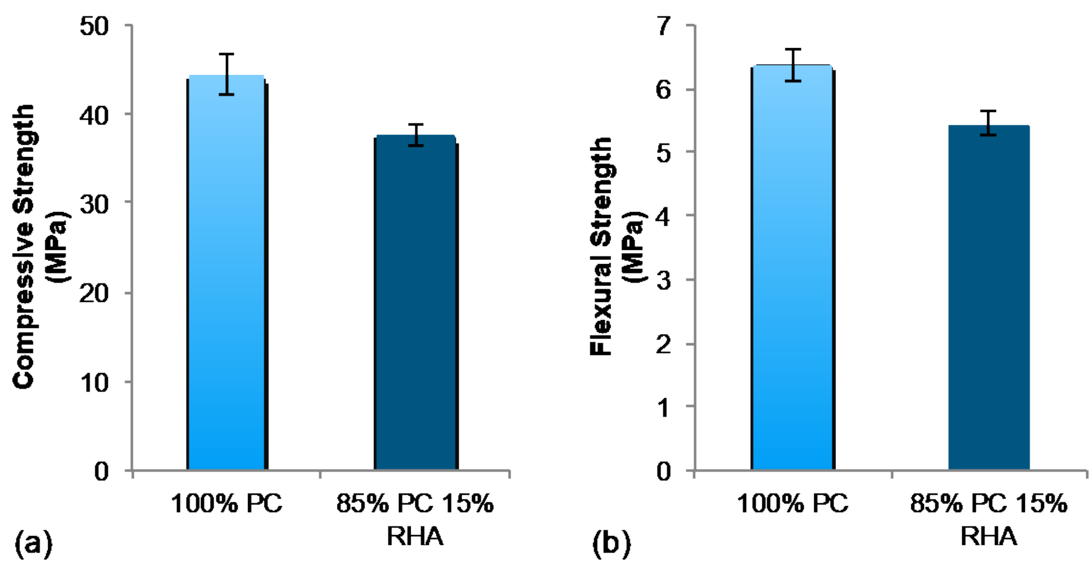


Figure 1. Compressive strength and flexural strength of concrete mixtures

4.2. Concrete Drying Shrinkage and Alkali-silica Reactivity

Preliminary durability-related tests of drying shrinkage and alkali-silica reactivity were promising for the use of rice ash in concrete. Testing a 15% replacement of cement with rice hull ash from conventional bioenergy production indicated that the use of rice hull ash resulted in similar shrinkage and alkali-silica reactivity to a concrete mixture containing Portland cement as the only component of the cement system (see Figure 2). Additional testing is underway to quantify sulfate resistivity and chloride ingress for concrete mixtures containing rice-based ashes.

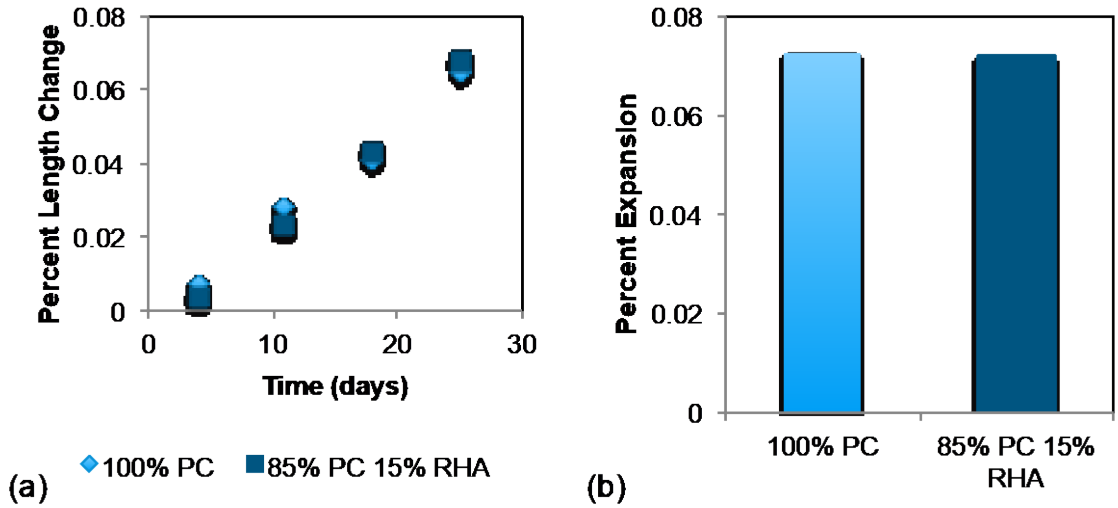


Figure 2. Percent change in length for concrete mixtures shown for (a) drying shrinkage and (b) alkali-silica reactivity

4.3. Leachate Characteristics

Leachate from rice hulls and rice straw leached with tap water or with acid solution were tested to determine the soluble minerals that were removed from the biomass. A table summarizing those soluble mineral compounds in the leachate and the final pH of the leachate are presented in Table 2. These results indicate that the leaching process removes potassium. Interestingly, the use of acid solution improves potassium leaching from hulls, but not the straw. Phosphoric acid had been selected for analysis because past studies indicated that high alkali-removal could be anticipated and high ash content would remain in the biomass after leaching [25]. However, it is possible that different leaching solutions would be better suited when potassium removal is being optimized. While the tap water removed more potassium from the rice straw than the acid solution, the use of acid leaching improves removal of most soluble elements examined.

Table 2. Soluble salt composition, micronutrient composition, and pH of water and acid leachates

	pH	K	Ca	Mg	Na	Zn	Cu	Mn	Fe
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Tap Water	7.52	1.08	12.8	6.44	20.01	0.006	<0.010	<0.005	<0.010
Tap Water - Hull Leachate	5.41	227.63	3.2	5.71	18.86	0.166	0.048	1.56	0.199
Tap Water - Straw Leachate	5.72	806.62	2.8	37.30	59.57	0.466	0.165	18.75	0.94
Phosphoric Acid Solution	1.1	1.11	11.8	5.71	18.63	0.033	0.038	<0.005	0.127
Phosphoric Acid Solution - Hull Leachate	1.14	340.41	54	28.07	21.62	0.697	0.117	11.594	2.358
Phosphoric Acid Solution - Straw Leachate	1.24	438.37	64.4	40.34	34.27	1.317	0.164	41.299	1.651

4.4. Summary of Findings from Survey and Flow-diagram of Factors in the Economic Feasibility Assessment

Based on responses from surveys, several key findings were noted for each of the sectors studied. For energy producers, leaching with acid may not be feasible at any of the stages in ash production. Energy producers also noted that storage of ash is difficult. While newer, more efficient bioenergy plants seem less concerned with deriving a profit from ash waste, older plants are interested in finding value in ash (note: this implies it may be of interest to newer plants in the future as well). For millers and those involved in hull management, the storage of raw material was noted as difficult for some, with millers highlighting this as an issue. Further, these groups mentioned that several other products using straw, hulls, and ash are either dwindling or are obtaining biomass at low prices. For straw balers, water leaching was noted as likely being too difficult to do in the fields. The balers also noted that other products using the biomass were obtaining it at low prices. For concrete suppliers, the key issue was obtaining ash with consistent properties and having consistent access to ash. Notably, concrete suppliers mentioned ash does not need to be a high performance additive (e.g., silica fume) if it can be a consistent pozzolan source for concrete and not exceed current pozzolan prices (~$100 / ton). Finally, concrete suppliers noted that the easiest way to transport ash from the bioenergy plants, i.e., moistened to reduce fly away, was of no concern. A flow diagram noting key phases in the processing/handling of the rice-based ashes is shown in Figure 3. Summaries of monetary takeaways for rice hull ash and rice straw ash are listed in Tables 3 and 4, respectively.

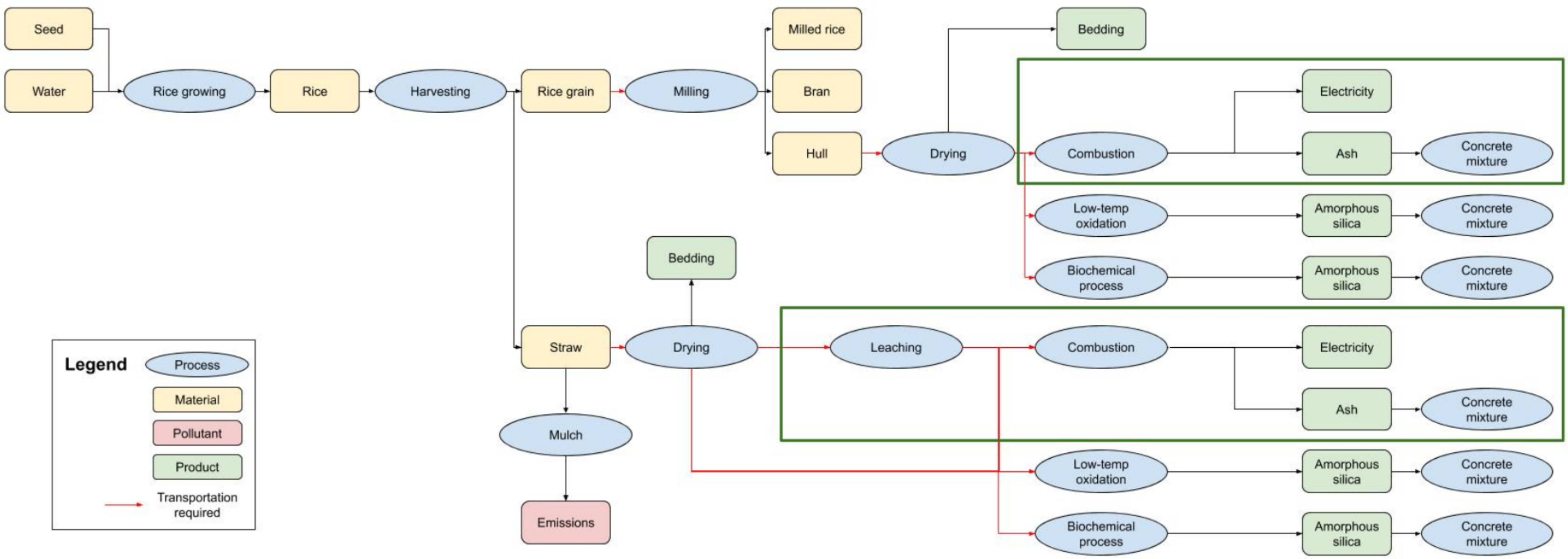


Figure 3. Initial flow diagram of key stages that could affect feasibility
(flows associated with fertilizers, herbicides, and other cultivation practices will be incorporated as will drying of leached biomass)

Table 3. Rice Hull Ash Summary Table

Step in Supply Chain	Price $	Alternative Price $
Rice Field Paddy		
Milling		
Hulls	$? Varying; sometimes get paid for hulls (not disclosed), sometimes pay to get rid of hulls	Cattle feed, poultry bedding, mulch, wine processing Negative to $0 to $16/ton
Biomass Energy Plant	Energy price: below $100/MWh, above solar $30-40/MWh; Cost of operation $50/MWh large plant; $180/MWh new small plant	Still evaluating for competitive feedstocks; lower burn temperature to produce reactive ash is feasible
Ash	Low carbon ash for concrete, usually no value at energy plant, cannot store	high carbon ash sometimes bought as soil amendment
Ready Mix Concrete Plant	?	$100/dry ton at concrete plant for Class F fly ash, ground blast furnace slag

Table 4. Rice Straw Ash Summary Table

Step in Supply Chain	Price $	Alternative Price $
Rice Field Straw		Leave
Baled Straw	Farmers pay baler $5 to $10/ton to remove	Cattle feed, animal bedding, wattles: $45 to $55/ton, wallboard (Williams) $30/ton
Chop/Grind/Leach K	Chop/grind cost about $8/ton Unknown cost of leaching, storing, drying	Liquid K 400-800 mg/L
Biomass Energy Plant	Energy price: below $100/MWh, above solar $30-40/MWh; Cost of operation $50/MWh large plant; $180/MWh new small plant	Still evaluating for competitive feedstocks; lower burn temperature to produce reactive ash is feasible
Ash	Low carbon ash for concrete, usually no value at energy plant, cannot store	high carbon ash sometimes bought as soil amendment
Ready Mix Concrete Plant	?	$100/dry ton at concrete plant for Class F fly ash, ground blast furnace slag

The economic feasibility and environmental impact assessments for this study are still underway. At present, we are incorporating potential changes to mechanical properties into value assessments, examining tradeoffs in transportation distances to assess regional value of RHA for concrete, and determining thresholds for desirable use of RSA in concrete. Further, knowing that potassium can be removed through a leaching processes, analysis of potential value of leachate as a fertilizer to inform co-product allocation is being conducted. For the environmental analysis, preparation of data for quantification of potential GHG emissions (and other critical environmental impacts) reduction value for

RHA/RSA as pozzolans in concrete using baseline comparisons of conventional mixtures is being performed.

5. Conclusions and Recommendations for Further Study

This work provides insight into the implications of altering biomass treatment and combustion temperatures as well as on the properties containing by-product ash. Continuing experiments will assess the effects of different ashes formed with each leaching condition and combustion temperature studied on cement-based mortar strength. Further, data collected will be used to perform an economic feasibility assessment. Finally, work has begun on determining environmental impacts of concrete containing rice-ash. In regions where agricultural residues are a potential fuel for bioenergy and/or a potential resource to meet growing demand for supplementary cementitious materials for concrete, the interdependent factors associated with how these resources are prepared could be a critical area to leverage in the design of energy and material systems.

Further study should be considered in a few areas that could support the feasibility of using rice-based ashes in concrete. These include, but are not limited to, further investigation into material properties, including assessment of how post-combustion treatments can improve consistency in ashes and additional investigation into other durability properties, especially if other ash preparation methods are used. Further investigation into analysis of co-products that can be formed in addition to rice-based ash should be considered, these may include exploration of what other co-products could be generated beyond the electricity and ash that could contribute to improved value and assessment of the extent to which these products might these mitigate costs and environmental impacts.

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