



Use of non-wood biomass combustion ash in development of alkali-activated concrete



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HIGHLIGHTS

- Effective use of the non-wood biomass ash chemistry in cementitious binders.
- Formulation of alkali aluminosilicate-based binders with non-wood biomass ash.
- Development of viable concrete materials with non-wood biomass ash raw materials.

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ABSTRACT

The work reported herein focuses on demonstrating the value of non-wood biomass combustion ash in production of alkali-activated concrete. The growing use of biomass as fuel leaves significant quantities of solid residue (ash) with qualities that are different from those of coal combustion ash. The composition of biomass ash suits development of alternative cement chemistries with significantly reduced carbon footprint and energy content when compared with Portland cement. Sustainable cement chemistries relying upon alkali aluminosilicate hydrate as the primary binder are receiving growing attention. Combustion ashes of wheat straw, switch grass, corn cob, alfalfa stem, corn stalk, cotton gin and rice hull were evaluated in this investigation. Characterization of the chemical composition, mineralogy, degree of crystallinity, solubility, pH in solution, loss on ignition, morphology and particle size distribution of non-wood biomass ashes, and the strength and moisture stability of the resulting concrete provided a basis for assessment of the merits of non-wood biomass ash as reactive raw materials in production of alkali-activated concrete.

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1. Introduction

Non-wood biofuels (e.g., agricultural wastes) are among alternative fuels that are carbon neutral. Extraction of value from biomass in biorefineries is a growing practice [1]. Combustion ashes are the by-products of biomass combustion in power plants and biorefineries [1]. The relatively high silica and alkali contents of non-wood biomass ash are of value towards production of alkali aluminosilicate hydrate-based binders for high-performance and sustainable concrete materials. Table 1 compares examples of ash contents and compositions in combustion of wood, wheat straw,

and algae. Combustion ashes of wheat straw and algae (examples of non-wood biomass) are distinguished from wood combustion ash by significantly reduced CaO contents, substantially increased SiO₂ and alkali (Na₂O + K₂O) contents, greater Cl contents (washing can lower the Cl content of ash [2]), and reduced heavy metal concentrations.

Coal fly ash is now used in massive quantities as a partial replacement for cement in concrete [3]. Major research investigations have thus focused on the potential value of biomass combustion ash as a supplementary cementitious material in conventional concrete [4–7]. While some promising results have been produced with wood combustion fly ash as replacement for ~10 wt% of cement, the relatively high alkali content of wood waste ash is a drawback for the concrete industry which is highly concerned with deleterious alkali-silica reactions. In the case of wood waste ash with moderately high alkali content, the relatively low C/S ratio

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Table 1
Characteristics of typical wood, agricultural waste and algae combustion ashes [2,3].

Biomass	Ash, wt% of fuel	Ash composition (wt% of ash)										
		CaO	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	Fe ₂ O ₃	MgO	Cl	SO ₃	P ₂ O ₅	GCV ^a
Wood	0.4	30	7	1	1	8	1	6	2	10	5	21
Wheat straw	6	7	52	3	2	23	1	2	6	9	3	19
Ulva lactuca (algae)	35	8	24	0	8	11	2	12	9	19	4	13

^a Gross calorific value, MJ/kg.

of the C–S–H generated by the pozzolanic reaction of the biomass ash enables binding of relatively high quantities of alkalis within the C–S–H structure [5]. This phenomenon controls the potential for deleterious alkali-silica reactions in concrete incorporating wood combustion ash as partial replacement for cement [5]. The high alkali contents of non-wood combustion ashes, however, seriously challenge the potential for their use as supplementary cementitious materials in concrete. An alternative approach for value-added use of non-wood biomass combustion ash, pursued in this study, takes advantage of the high alkali content of biomass ash towards producing structural grade binders based on alkali aluminosilicate hydrates. This activation process involves reactions between non-wood biomass ash, which can be classified (either inherently or after augmentation) as an aluminosilicate (AS_y), and an alkali silicate solution [RS_z(aq.)] (typically blended with alkali hydroxide) in water (H): AS_y + RS_z(aq.) + nH → RAS_(y+z)H_n. This is a polycondensation reaction in which the dissolved alkali silicate cross-links with the reactive aluminosilicate to form high-performance solid structures with significant binding attributes [3]. The alkalis in biomass ash feasibly take part in this reaction. The resulting hydrates incorporate relatively low chemically bound water contents when compared with the hydration products of Portland cement.

Binders based on alkali aluminosilicate hydrates offer the potential to yield lower carbon footprint and energy content when compared with Portland cement [8–10]. Unlike the 1D structure of calcium silicate hydrate, the primary binder among ordinary cement hydrates, which relies upon weak secondary bonds to form a 3D structure, alkali-activated aluminosilicates form an extended 3D structure with primary bonds via polycondensation [11,12].

Alkali-activated aluminosilicate binders are formed by through-solution chemical reactions between the dissolved constituents of various aluminosilicate precursors with alkaline earth and alkali metal cations that are present in an alkaline solution [13]. These reactions yield predominantly alkali and calcium aluminosilicate hydrates [14], and tend to occur at higher rates than hydration of ordinary Portland cement. The extended 2D/3D structure of calcium/alkali aluminosilicate hydrates, and their relatively low content of chemically bound water, distinct molecular-scale porous morphology and robust chemistry explain their advantages over the hydration products of ordinary Portland cement (primarily calcium silicate hydrate). Some key performance advantages of alkali-activated aluminosilicates are: (i) stability under weathering and chemical attack; (ii) impermeability; (iii) encapsulation of hazardous materials; (iv) fire resistance; (v) abrasion/erosion resistance; (vi) dimensional stability; (vii) rate of strength gain and ultimate strength; and (viii) adhesion and binding qualities [15–19]. The potential for reducing carbon footprint and energy content are also among the advantages of alkali-activated aluminosilicate binders versus ordinary Portland cement hydrates [8,9]. Continued hydration of ordinary Portland cement requires input of moisture to retain close to 100% relative humidity, which challenges practical achievement of advanced hydration states in field conditions. The alkali-activated aluminosilicate binder structure, on the other hand, continues to develop in ambient condition without the need for external input of moisture; this is because

water is consumed and then regenerated in alkali-activation of aluminosilicates [11].

The work reported herein has developed alkali-activated aluminosilicate binders for concrete production which by making value-added use of the combustion ashes of non-wood biomass which are rich in silica, alkalis, and (to a lesser extent) alumina. Non-wood biomass ash is formulated with supplementary materials in order to achieve a desired chemical balance and particle size distribution for production of high-performance, low-cost, sustainable and environmentally safe alkali-activated biomass ash-based concrete.

2. Value of non-wood biomass ash in production of alkali-activated aluminosilicate binders

Alkali-activated materials encompass binder systems derived by reaction of an alkaline salt with a solid silicate powder. The alkaline salts used in the process are essentially any soluble substance which can raise the pH of the reaction mixture and accelerate dissolution of the solid precursor. When compared with ordinary Portland cement, alkali-activated binders have a high degree of silicate connectivity, and a higher ratio of (SiO₂ + Al₂O₃) to (CaO + Na₂O). While alkali-activated binders tend to have lower calcium contents than Portland cement binders, the presence of calcium is important to the stability and long-term performance of alkali-activated binders [20,21]. These binders assume a high degree of moisture resistance and chemical stability as far as they can produce a highly coordinated (overwhelmingly Q⁴) ‘geopolymeric’ structure. Alkali-activated materials with relatively high aluminum contents can assume this ‘geopolymeric’ structure. Fig. 1 shows the calcium and aluminum contents of geopolymer

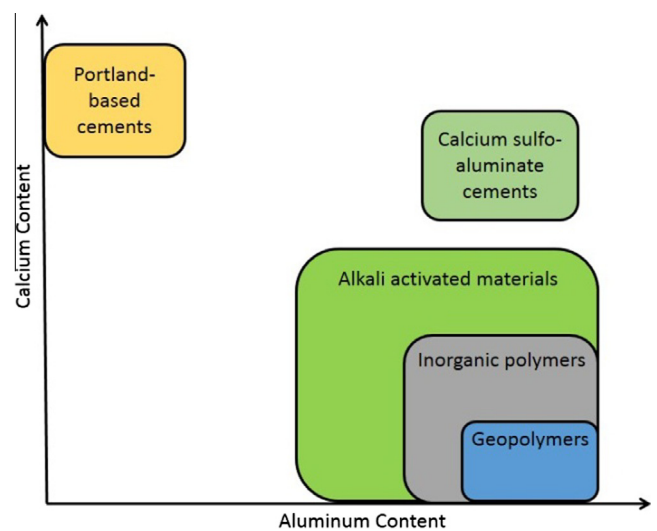


Fig. 1. Classification of different subsets of alkali-activated materials, with comparisons to ordinary Portland cement and calcium sulfoaluminate binder chemistry (darker shading corresponds to higher concentrations of Na and/or K) [19].

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