Waste peat ash mineralogy and transformation to microporous zeolites

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Abstract

The combustion of peat fuel for industrial scale power generation and domestic heating produces toxic ash, most of which is presently buried in landfill. In this study, the mineralogy of waste peat ash was determined, followed by its successful use as a starting reagent to prepare zeolites. X-ray diffraction (XRD) confirmed the presence of quartz, anhydrite, calcite, lime, merwinite and magnetite in peat ash, and that a single extraction step using mineral acid was sufficient to remove all non-quartz crystal phases. Alkali fusion of the acid-extracted samples produced GIS-type zeolite. LTA- and FAU-type were also prepared by altering the Si/Al ratio and extending the ageing time. Experiments confirmed that the LTA- and FAU-type zeolites were active in the simultaneous adsorption of lead, cadmium, cobalt, zinc and copper from aqueous solutions, with similar quantities of metals removed to those using a reference zeolite.

Keywords; Peat ash utilisation; zeolite; pyrolysis; waste management; water purification.

1. Introduction

Peat is a carbon based material produced from partially decayed vegetation that builds up over a duration typically up to approximately 12,000 years [1,2]. The deficiencies of oxygen and nutrients in waterlogged bogs and fens (peatlands) limit the decay rate of vegetation such that there is an accumulation of peat over time. These peatlands cover an estimated global area of 4m km^2, which equates to 2-3% of the total land area, and are found mainly in Russia, North and South America, Northern Europe and South-East Asia, including lower quantities in locations such as central Africa [1,2]. Peat is classified as an intermediate fuel i.e. between biomass and fossil fuel (lignite). Total global consumption is estimated at 17m tons per annum, over 99% of which is used in Northern Europe for the production of heat and electricity [3]. Ireland is the largest user, consuming 3.8m tons annually from peatlands that cover approximately 20% of the national land area [4]. Most of this is used in thermal power plants to generate 8.5% of Ireland's electricity [5,6]. While renewable fuel sources are increasingly being used as a substitute for peat (at least partially in the short term), the production of electricity in Ireland using peat based fuel is an established industry with a secure, indigenous energy source, and will, therefore, continue for the foreseeable future.

Peat ash is the main waste product of combustion at thermal power stations, some of which is disposed of by landfill burial. The alkalinity of peat ash alters the soil quality of the landfill site such that only alkali tolerant plants can grow during the years immediately after disposal. The composition of peat ash varies with location but typically contains a mixture of silicon-, aluminium-, calcium- and iron-containing species, and a range of toxic elements including arsenic and cadmium [7-10]. While its elemental composition has been well studied, a definitive characterisation of peat ash mineralogy is lacking in the literature. The few papers that discuss peat ash infer crystal phases from (a) elemental composition by scanning electron microscopy/energy-dispersive X-ray spectroscopy (SEM/EDAX) or X-ray fluorescence (XRF)

only and/or (b) unseen XRD data; the reader is thus advised to treat such assertions with caution. For example, quartz, microcline, albite and calcium sulfate were reported to be present in peat ash samples, although no XRD results were shown [7, 8].

The transformation of peat ash to a useful value-added product with industrial applications would be a significant improvement on the current method of disposal. One such possibility is to use peat ash to prepare zeolites, which are high surface area aluminosilicates widely used for water treatment and purification, humidity control, and heterogeneous catalysis [11]. The combustion of fossil fuels and biomass produces ash residue that contains silicon and aluminium based minerals in appropriate quantities to those used to prepare aluminosilicate zeolites. Coal fly ash has been extensively studied as a zeolite synthesis reagent, and a variety of zeolite architectures were successfully prepared using the alkali fusion method [12-23]. More recently, there are reports showing zeolite preparation using ash from the following renewable biomass sources: rice husk [24-27] eucalyptus bark residue [28], pulp from paper industry [29], sawdust and pine bark [30], bamboo [31] and cogon grass [32].

We now report the mineralogy of peat ash and its successful transformation to pure zeolite using a single stage purification step. To our knowledge, this is the first report of zeolite prepared using peat ash. The zeolites formed removed heavy metals from aqueous solution with practically similar quantities to those of a reference zeolite.

2. Materials and Methods

2.1 Materials

Peat ash, from Ireland, was collected and combusted as follows: (a) sample A (lime added), *Bord na Móna ltd.*, industrial boiler (b) sample B, air-dried peat sods from county Roscommon, domestic stove. The following is a list of the materials' source/supplier and purity; hydrochloric acid (HCl), concentration >37%, Fluka; nitric acid 70% w/w; sodium hydroxide (NaOH)

pellets (anhydrous), extra pure, Sigma-Aldrich; sodium aluminate ($NaAlO_2$), general purpose, Fischer; sodium silicate solution, general purpose, Merck. Copper(II) nitrate trihydrate $Cu(NO_3)_2.3H_2O$, cobalt(II) nitrate hexahydrate $Co(NO_3)_2.6H_2O$, lead nitrate $Pb(NO_3)_2$, zinc nitrate hexahydrate $Zn(NO_3)_2.6H_2O$ and cadmium nitrate tetrahydrate $Cd(NO_3)_2.4H_2O$ were all 99.99% purity and supplied by Sigma-Aldrich.

2.2 Zeolite synthesis

The samples were calcined in air at 600 °C (sample A) and 800 °C (sample B) for 4 h to remove organic matter. Acid extraction was conducted by treating 30 g of calcined peat ash in 500 cm^3 acid for 5 h as follows: Sample A was stirred in 5 M HNO_3 at room temperature, and sample B was refluxed in 5 M HCl at 95 °C. The product was recovered by filtration and dried at 80 °C. Unless otherwise stated, 1 part of the acid extracted ash was ground in a mortar and pestle with 2.4 parts (by mass) NaOH, heated at 600 °C in air for 3 h in a furnace, and crushed to powder form after cooling to ambient temperature. 1 part alkali fused ash was then added to 10 parts water in a polypropylene bottle, stirred at room temperature for 3 days, and hydrothermally treated at 90 °C for 24 h. Sodium aluminate was added prior to alkali fusion to give Si/Al ratios (of synthesis reagents) of 5 and 1 to produce GIS and LTA, respectively. Additional ageing of the Si/Al ratio 1 suspension was done for 4 days at 35 °C to produce FAU. Products were recovered by filtration and calcined in air at 550 ºC for 4 h using a ramp rate of 5 °C min^{-1}. A reference FAU zeolite was prepared from a synthesis solution with the molar composition $8NaOH : 0.2Al_2O_3 : 1.0SiO_2 : 200H_2O$ [33]. The hydrothermal treatment was performed at 80 °C for 24 h.

2.3 Characterisation

XRD was conducted in ambient conditions using a Panalytical X'Pert Powder diffractometer with Cu Kα radiation (λ = 1.5406 Å). All powder diffraction patterns were recorded from 4 to 120° 2θ with step size 0.013 ° and step time 50 s, using an X-ray tube operated at 40 kV and 30 mA with fixed ¼ ° anti-scatter slit. A Rigaku NEX-CG (XRF) spectrometer was used for elemental analysis using the loose powder method under vacuum. Nitrogen adsorption/desorption measurements were carried out using a Micromeritics ASAP 2020 surface area analyser at -196 °C. Samples were degassed under vacuum ($p < 10^{-5}$ mbar) for 5 h at 200 °C prior to analysis. Brunauer–Emmett–Teller (BET) surface areas of the samples were calculated in the relative pressure range 0.05-0.30. Microscopic images were recorded using a JEOL JSM-5600LV SEM.

2.4 Adsorption study

$Cu(NO_3)_2.3H_2O$, $Co(NO_3)_2.6H_2O$, $Pb(NO_3)_2$, $Zn(NO_3)_2.6H_2O$ and $Cd(NO_3)_2.4H_2O$ were dissolved together in water and diluted to give a solution that was 100 ppm in each of Cu, Co, Pd, Zn and Cd. 20 cm^3 of this solution were added to 0.1 g LTA (sample A), stirred at 180 rpm for 1 h at room temperature and the solid removed by filtration**.** The concentrations of metals before and after adsorption were determined using a Thermo Scientific iCAP 6000 Series inductively coupled plasma-optical emissions spectrometer (ICP-OES).

3. Results and Discussion

3.1 Crystallography and elemental composition

SEM images, Fig. 1, show that both raw and calcined peat ash lack any regular morphology, which is in contrast to the spherically shaped particles routinely observed for coal fly ash [12]. Results also showed that calcination did not cause an observable transformation in particle morphology. Phase identification, performed by matching the XRD peak positions in Fig. 2

against the Crystallography Open Database, confirms that the major phases detected for sample A are anhydrite ($CaSO_4$), quartz (SiO_2), calcite ($CaCO_3$), lime (CaO) and merwinite ($Ca_3Mg(SiO_4)_2$). Sample B contains anhydrite, quartz and magnetite (Fe_3O_4). A quantitative elemental analysis using XRF, Table 1, shows the 10 most concentrated elements present (for sample A) and confirms that the major 'impurities' (in terms of zeolite synthesis) are Ca and Fe based species. The major element present in Sample A is Ca at 53.9 wt% (as oxide) in agreement with the XRD analysis (Fig. 2). Sample B contains 21.2 wt% CaO and 22.0 wt% Fe_2O_3. The greater quantity of CaO in sample A is due to the addition of lime to commercial peat to reduce SO_x emissions, which may have reacted to produce anhydrite. It is interesting then that sample B, which has not been treated with lime, also contains anhydrite.

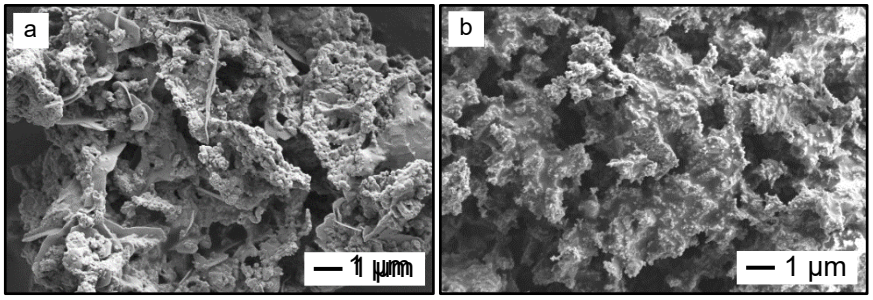


Fig. 1. Typical SEM images of peat ash: (a) raw and (b) calcined.

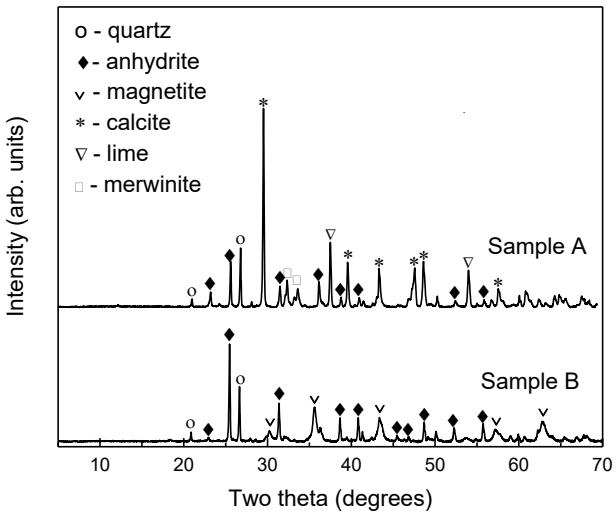


Fig. 2. XRD powder patterns of calcined peat ash.

It is not possible to make a meaningful comparison of the XRD results presented here with published data on peat ash mineralogy, as such reports contain insufficient results [7,8]. However, all such studies confirm that the main elements present in peat ash are Ca, Fe, Si and Al, which correlates well with our XRD and XRF results.

Table 1: XRF elemental composition of peat ash in wt% following calcination and acid extraction.

	A		B	
	Calcined	**Acid extracted**	**Calcined**	**Acid extracted**
CaO	53.9	0.81	21.2	0.77
SiO_2	9.47	71.4	12.7	76.9
SO_3	7.32	0.58	22.4	0.26
Fe_2O_3	4.81	1.29	22.0	0.61
MgO	2.20	0.12	10.4	0.35
Al_2O_3	1.63	2.55	6.58	3.77
MnO	0.35	0.03	0.30	0.02
P_2O_5	0.26	0.05	1.87	0.05
K_2O	0.19	0.97	0.97	1.12
TiO_2	0.15	0.50	0.45	0.90

Dissolution by acid extraction considerably reduced the quantities of Ca and Fe in both samples. The Si/Al ratios of acid extracted peat ashes are 28.0 for sample A and 20.4 for sample B. XRD patterns confirm that acid extraction removes all detectable non-quartz crystalline phases, Fig. 3. The majority of zeolite preparations using coal ash do not remove impurities by acid extraction, so it is not surprising that a greater ratio of NaOH to ash is required for the peat ash samples explored here to achieve full quartz decomposition due to the higher quantity of quartz [12]. Fig. 3 shows that the mass ratio of 1.2:1 NaOH to ash (chosen as a starting point based on reference [22]) was insufficient but that higher ratios removed quartz completely; a mass ratio of 2.4:1 was used in all further preparations. The other peaks in Fig. 3 confirm the presence of silicates and aluminosilicates, as reported in the literature [34].

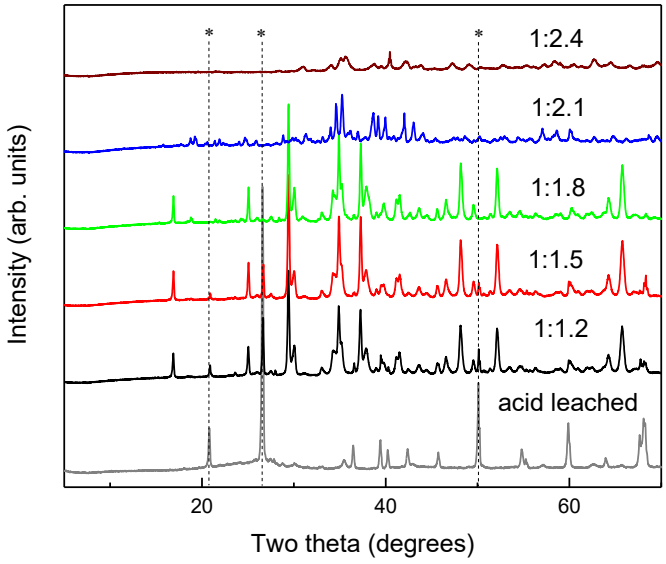


Fig. 3. XRD patterns of sample A after acid leaching and the acid-leached sample after alkali fusion at 600 °C using different sample:NaOH mass ratios as indicated on the figure; the asterisks indicate quartz peaks.

3.2 Zeolite formation

The XRD patterns in Figs. 4 and 5 confirm that peat ash was transformed to zeolite frameworks GIS, LTA and FAU through changes in the synthesis parameters viz. addition of sodium aluminate for LTA, and extended ageing time for FAU. Non-zeolitic crystalline phases were not observed by XRD in any detectable quantities. The effect of altering the Si/Al ratio by adding external silica was found to alter the crystal phase produced in a study of the crystallisation mechanism of zeolite from coal fly ash, where FAU was not formed until the Si/Al ratio was reduced to approximately 1.5 [35]. SEM images, Fig. 6, show the morphology of GIS, the characteristic cubic ca. 1 μm sized particles of LTA and the sub-micron agglomerated FAU particle morphology, providing further evidence of the presence of these phases. The Si/Al ratios are shown in Table 2: the Si/Al ratios of FAU are 1.32 and 1.35, so these samples are zeolite X. The highest BET surface areas were recorded for the FAU structures, which were calculated to be 486 and 319 $m^2 g^{-1}$.

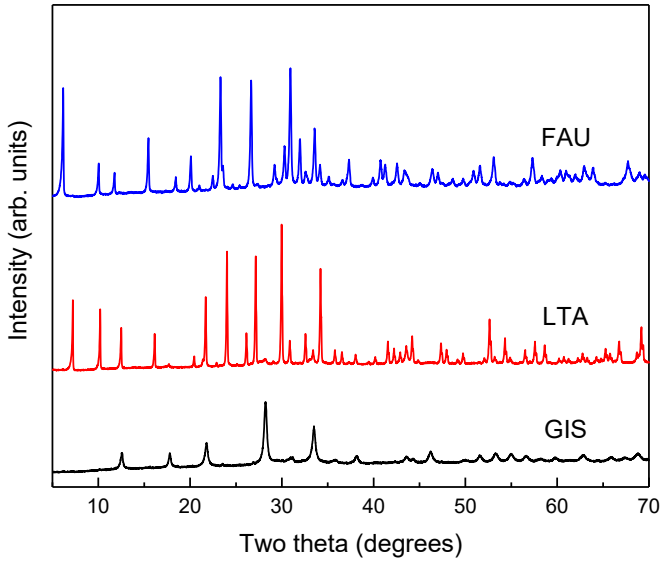


Fig. 4 XRD patterns of zeolites prepared using sample A.

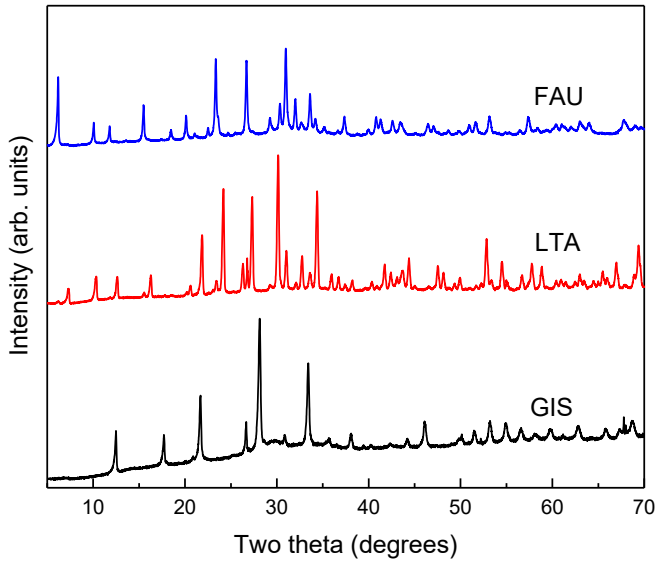


Fig. 5 XRD patterns of zeolites prepared using sample B.

Table 2: BET surface areas and Si/Al elemental ratios.

	Surface area (m^2 g^{-1})		Si/Al	
	A	**B**	**A**	**B**
Raw	24	25	4.04	1.55
Calcined	6	22	4.94	1.64
FAU	486	319	1.32	1.35
LTA	84	55	1.41	1.35
GIS	77	104	2.83	2.83

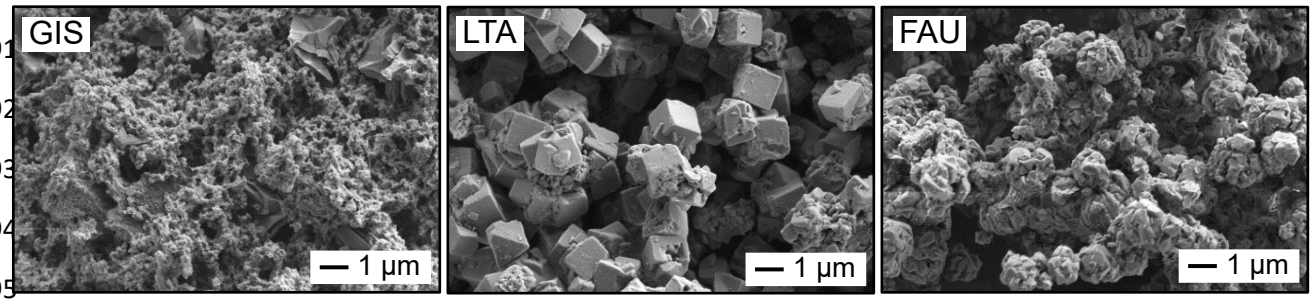


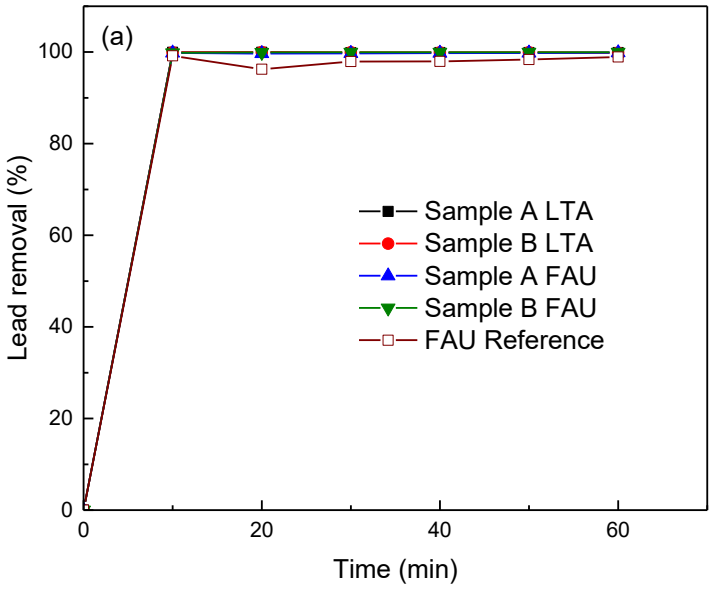
Fig. 6. Typical SEM images of different zeolites types prepared from peat ash.

The characteristics of zeolites prepared from peat ash also compare well with analogous studies using fly ash. For example, the highest surface area reported by Tosheva et al. for FAU prepared from fly ash was 441 m^2 g^{-1}, relative to 486 m^2 g^{-1} for that prepared here [23]. The classification of coal is based on the relative amounts of organic and inorganic materials, age, and quantity of heat energy that can be produced. Most reports in the literature describing coal ash to zeolite conversions are for sub-bituminous (up to 45% carbon) bituminous (86%) and anthracitic (97%) coal types. Lignite has lower carbon content than sub-bituminous coal and, because it is formed over time from compressed peat, which has carbon content less than 40-55%, seems the most appropriate comparison to the results presented here [1-3]. Kunecki et al. used lignite, containing quartz, anhydrite and gehlenite, to prepare zeolite [36]. Both LTA and FAU frameworks were prepared by varying experimental conditions, but not in pure form. The highest BET surface area for FAU was 256 m^2 g^{-1}, which was significantly lower than the FAU

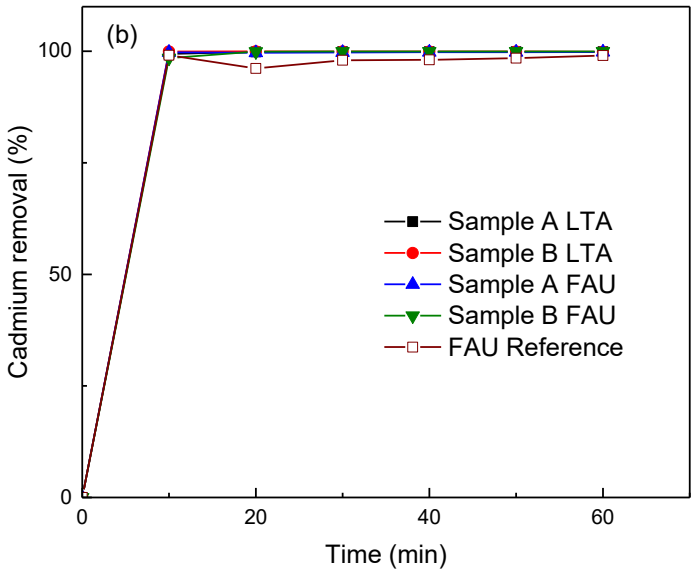
from either sample in this study, 486 and 319 $m^2 g^{-1}$. The increased crystal purity and surface area for zeolite prepared using peat ash is tentatively attributed to the removal of impurities in the starting material by acid extraction. Anhydrite is highly soluble in aqueous solution and its presence during zeolite crystallisation, as in the case of lignite to zeolite, reduces the solubility of silicates and aluminosilicates, which will negatively impact both the formation of zeolite nuclei and the subsequent dissolution and crystallisation of zeolite during hydrothermal treatment. Furthermore, ions in solution are known to interact with zeolite frameworks during crystallisation, so the Ca^{2+} and SO_4^{2-} ions from anhydrite may have a negative effect on the formation of zeolite [37].

3.3 Adsorption study

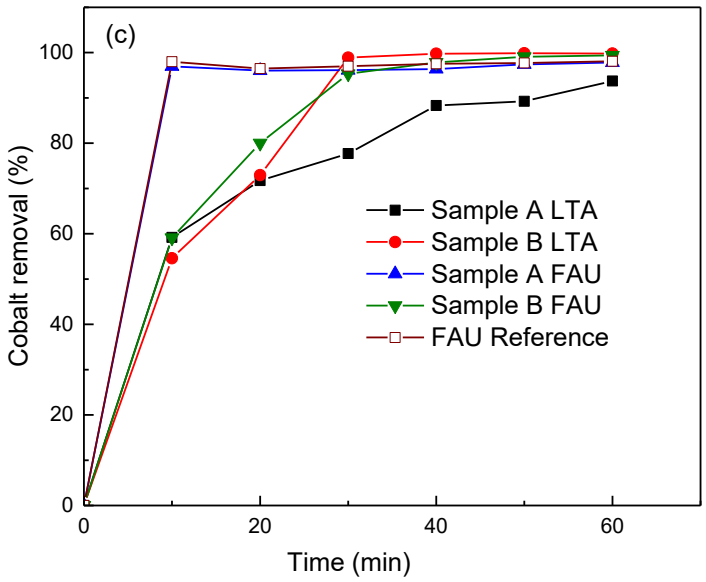
The prepared zeolites were tested as adsorbents in the removal of heavy metals lead, cadmium, cobalt, zinc and copper from aqueous solution; these metals were chosen on the basis of their toxicity and presence in wastewater streams [38]. The results, Fig. 7, showed that all zeolites actively removed the range of metals between 10 and 60 minutes, in which the quantities of lead, cadmium, zinc and copper adsorbed using peat ash prepared zeolites were slightly higher than those measured for the FAU- reference. In the case of cobalt, adsorption was higher using FAU-type zeolites than LTA-, while the most active adsorbent was that prepared from sample A, which showed near identical properties to that of the reference zeolite. A more in-depth study of metals adsorption on zeolites viz. influence of concentration, temperature, and kinetics is currently underway and will be published as a follow up to this paper. While the focus of this paper is the preparation of pure zeolite from peat ash, the adsorption results are included to validate the efficacy of such materials in real applications.


(a)
Lead removal (%)
Time (min)
Sample A LTA
Sample B LTA
Sample A FAU
Sample B FAU
FAU Reference
0
20
40
60
80
100
0
20
40
60

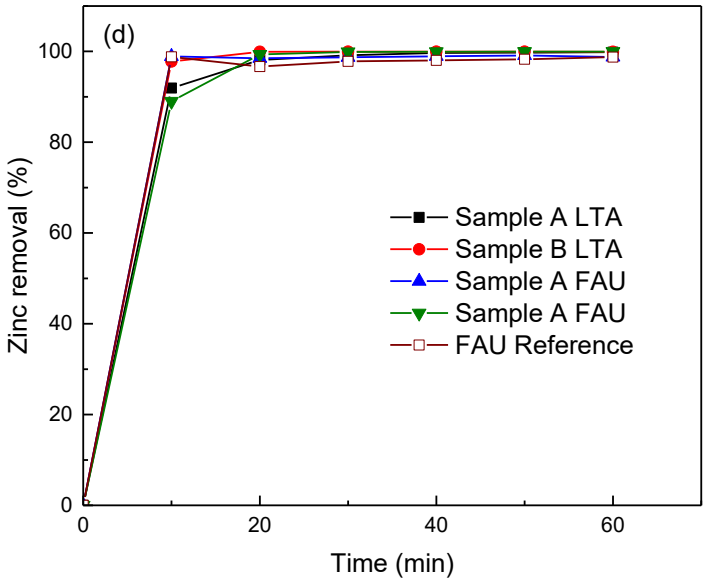
233


(b)
Cadmium removal (%)
Time (min)
Sample A LTA
Sample B LTA
Sample A FAU
Sample B FAU
FAU Reference
0
50
100
0
20
40
60

234


(c)
Cobalt removal (%)
Time (min)
Sample A LTA
Sample B LTA
Sample A FAU
Sample B FAU
FAU Reference
0
20
40
60
80
100
0
20
40
60

235


(d)
Zinc removal (%)
Time (min)
Sample A LTA
Sample B LTA
Sample A FAU
Sample A FAU
FAU Reference
0
20
40
60
80
100
0
20
40
60

236

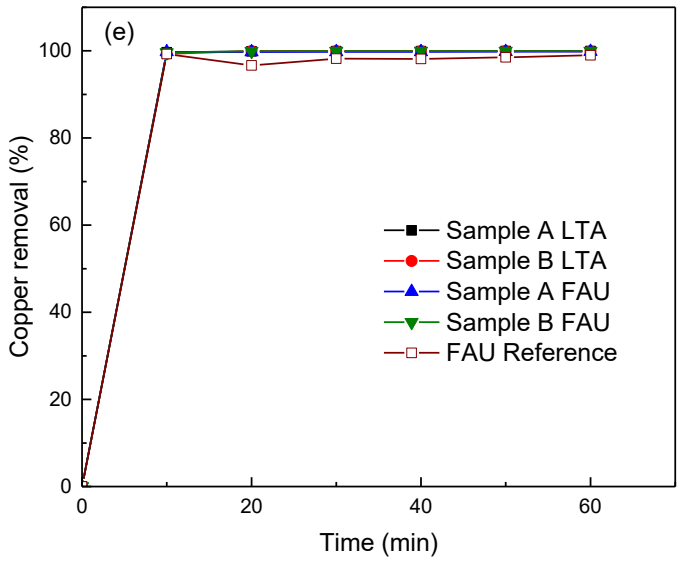


Fig. 7. Metal removal (as % of original concentration) of (a) lead (b) cadmium (c) cobalt (d) zinc and (e) copper on LTA- and FAU-type zeolites prepared from peat ash and an FAU- reference.

4. Conclusions

Zeolites were successfully prepared from peat ash using a combination of acid leaching, alkali fusion and hydrothermal treatment. The framework structure was systematically varied such that crystal phases of GIS, LTA and FAU-type zeolites were each prepared. The prepared zeolites were active in the removal of a range of metals from aqueous solution.

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