Tutkimuksia: Vähähiilinen betoni Geopolymeerit

POHJOIS-SUOMEN RAKENNUSKLUSTERI RY

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Sisällys

1. Tampereen yliopisto

- **Vähähiilisen betonin käyttö elementtikerrostalorakentamisessa hiilijalanjäljen näkökulmasta, Tuomas Laitinen**

  https://trepo.tuni.fi/bitstream/handle/10024/154295/LaitinenTuomas.pdf?sequence=2&isAllowed=y

  Ilmastonmuutos on jatkunut jyrkkää kehitystään esiteollisesta ajasta lähtien ja tilanne on käymässä kestämättömäksi. Maailman päättävät elimet ovat reagoineet ilmastonmuutoksen pysäyttämiseksi. Rakennusala on yksi suurimmista päästöjen aiheuttajista maailmanlaajuisesti ja siksi sen hiilijalanjäljen rajoittamiseksi on ryhdytty toimiin. 2025 tammikuussa astuu Suomessa voimaan uusi rakentamislaki, joka asettaa vaatimuksen ilmastoselvityksestä, materiaaliselosteesta sekä mahdollisuuden asettaa hiilikaton rakentamisluvan myöntämiseksi. Lisäksi kaavoitus vaatii enenevissä määrin puun käyttöä kerrostalorakentamisessa, mikä nostaa rakentamisen kustannuksia betonirakentamiseen verrattuna.

  Tilanne asettaa rakennuttajille paineita varautua tulevaisuuden haasteisiin selvittämällä keinoja rakentamisen elinkaaren hiilipäästöjen vähentämiseksi. Tämä tutkimus keskittyy erityisesti kerrostalorakentamisen materiaalien tuotevaiheen hiilipäästöjen arviointiin sekä keinoihin laskea betonirakentamisen hiilipäästöjä vähähiilisen betonin avulla. Päätavoitteena on selvittää, voidaanko betonirakentamisessa tällä hetkellä vähähiilistä betonia hyödyntämällä päästä puutaloa vastaavaan hiilijalanjälkeen. Sivutavoitteena on kartoittaa vähähiilisen betonin käytön kustannuksia tämän hetken markkinoilla.

  Tutkimuksen teoriaosuudessa käsitellään syitä rakennuslain muutokselle, tutustutaan rakennushankkeen hiilipäästöjen jakautumiseen, vähähiiliseen betoniin ja selvitetään, kuinka rakennuksen elinkaaren hiilijalanjälki arvioidaan.

  Tutkimuksen käsittelyosuudessa tutkitaan kolmea lähes identtistä T2H Pirkanmaa Oy:n kerrostaloa. Näistä yksi on puutalo, toinen hybriditalo ja kolmas betonitalo. Betonitalo on hybriditalon teoreettinen variantti. Näille lasketaan kullekin Ympäristöministeriön menetelmän mukaiset elinkaaren hiilijalanjälkiarviot Suomen kansallista päästötietokantaa hyödyntäen. Näitä tutkitaan ja vertaillaan rakennetasolla toisiinsa.

  Tutkimuksessa ilmenee, että vähähiilisellä betonilla ei voi tällä hetkellä päästä puurakentamista vastaaviin päästölukemiin ja vähähiilistä betonia pystyy ylipäänsä käyttämään vain runkorakenteissa. Betonitalon kokonaishiilipäästöjä onnistuttiin tiputtamaan noin 5 %. Materiaalien hiilipäästöt tippuivat 16,5 % vähähiilistä betonia hyödyntämällä. Kohderakennuksissa puutalon materiaalien hiilijalanjälki oli 33 % perinteisestä betonista valmistetun materiaalien hiilijalanjälkeä pienempi. Vähähiilisen betonin käytön todettiin nostavan betonituotteen hintaa noin 5–10 %.

Lisähuomiona tutkimuksessa havaittiin, että hybridirakentamisessa voisi tällä hetkellä olla vähähiilistä betonia suurempi potentiaali päästöjen vähentämisessä.

The use of low-carbon concrete in element apartment building construction from the perspective of carbon footprint, Tuomas Laitinen

Climate change has continued its steep trajectory since the pre-industrial era, and the situation is becoming unsustainable. Global governing bodies have responded to mitigate climate change. The construction industry is one of the largest contributors to emissions worldwide, prompting measures to limit its carbon footprint. In January 2025, a new construction law will come into effect in Finland, mandating climate assessments, material declarations, and the option to set a carbon cap for construction permits. Additionally, urban planning increasingly requires the use of wood in apartment building construction, leading to higher costs compared to concrete construction.

This situation places pressure on developers to prepare for future challenges by exploring methods to reduce carbon emissions throughout the construction lifecycle. This research focuses specifically on assessing the carbon emissions in the product phase of materials used in apartment building construction and exploring ways to reduce carbon emissions in concrete construction using low-carbon concrete. The main objective is to determine whether, by currently utilizing low-carbon concrete in concrete construction, it is possible to achieve a carbon footprint like that of a wooden house. A secondary objective is to investigate the costs associated with the use of low-carbon concrete in the current market.

The theoretical part of the research discusses the reasons for changes in building regulations, explores the distribution of carbon emissions in construction projects, introduces low-carbon concrete, and explains how the carbon footprint of a building's lifecycle is assessed.

In the practical part of the research, three nearly identical apartment buildings from T2H Pirkanmaa Oy. are examined. One is a wooden house, another is a hybrid house, and the third is a concrete house—a theoretical variant of the hybrid house. The carbon footprint estimates for each building are calculated using the methodology of the Finnish national emission database. These estimates are then analyzed and compared at the building level.

The research reveals that, at present, low-carbon concrete cannot achieve emissions comparable to wooden construction, and low-carbon concrete can only be feasibly used in structural elements. The total carbon emissions of the concrete building were reduced by approximately 5%, and material emissions were reduced by 16.5% with low-carbon concrete. In terms of material carbon footprint, the wooden house had a 33% lower footprint than traditional concrete. The use of low-carbon concrete was found to increase the price of concrete products by approximately 5– 10%.

As an additional observation, the research suggests that hybrid construction may currently aggregate concretehave greater potential for emissions reduction compared to the use of low-carbon concrete. Vähähiilisen betonin käyttö elementtikerrostalorakentamisessa hiilijalanjäljen näkökulmasta

2. Oulun yliopisto

- **Using recycled aggregate concrete at a precast-concrete plant: A multi-criteria company-oriented feasibility study/ Victor Revilla-Cuesta, Francisco Fiol, Priyadharshini Perumal, Vanesa Ortega-Lopez, Juan M. Manso**

  https://oulurepo.oulu.fi/bitstream/handle/10024/33493/nbnfi-fe2022111866138.pdf?sequence=1&isAllowed=y

  Numerous test results at laboratory scale confirm the utility of Recycled Aggregate (RA) for the development of concrete that demonstrates durability and adequate in-fresh and mechanical behavior. However, feasibility evaluations of the use of RA in real industrial applications are necessary, before any large-scale industrial application of these products can begin. In this research, the feasibility of producing precast-concrete components containing large amounts of coarse RA at a precast-concrete plant is analyzed. Two Self-Compacting Concretes (SCC) were produced, incorporating 0% and 100% coarse RA, respectively, at both laboratory scale (0.08 m3) and industrial scale (2 m3). Work took place at the industrial-scale facilities of a precast-concrete company that was collaborating in this study. Flowability and mechanical behavior were maintained as concrete production volumes increased, and concrete strength even increased after adding coarse RA, due to a careful mix design. However, the durability performance worsened by around 20% when produced at industrial scale, being this worsening higher whether coarse RA was used. A Multi-Criteria Decision-Making (MCDM) analysis, in which the criteria of the precast-concrete company defined the relative importance of each concrete property, showed the feasibility of manufacturing precast-SCC components containing coarse RA for interior usage, whose fundamental requirement is adequate mechanical strength. The results of the MCDM analysis also underlined the lower cost of coarse RA, making its use in SCC components cast with large concrete volumes advisable. Overall, the addition of coarse RA in the precast-concrete industry is recommended in the interests of a greener construction sector.

  Kierrätysaggregaatteja sisältävän betonin käyttö betonituotetehtaassa: monikriteerinen yrityslähtöinen toteutettavuustutkimus/ Victor Revilla-Cuesta, Francisco Fiol, Priyadharshini Perumal, Vanesa Ortega-Lopez, Juan M. Manso

  Lukuisat laboratoriomittakaavan testitulokset vahvistavat kierrätetyn kiviaineksen (RA) käyttökelpoisuuden betonin valmistuksessa, joka osoittaa kestävyyttä sekä riittävän tuore- ja mekaanisen käyttäytymisen. Kuitenkin kierrätetyn kiviaineksen käytön toteutettavuuden arviointi todellisissa teollisissa sovelluksissa on

välttämätöntä ennen kuin näiden tuotteiden laajamittainen teollinen käyttö voidaan aloittaa. Tässä tutkimuksessa analysoidaan mahdollisuutta valmistaa esivalmistettuja betonikomponentteja, jotka sisältävät suuria määriä karkeaa kierrätyskiviainesta (RA), esivalmistetun betonin tehtaalla. Kaksi itsetiivistyvää betonia (SCC) valmistettiin siten, että ne sisälsivät vastaavasti 0 % ja 100 % karkeaa kierrätyskiviainesta sekä laboratoriomittakaavassa (0,08 m³) että teollisessa mittakaavassa (2 m³). Työ toteutettiin tutkimukseen osallistuneen esivalmistetun betonin valmistajan teollisen mittakaavan tuotantolaitoksissa. Valettavuus ja mekaaninen käyttäytyminen säilyivät, kun betonin tuotantomääriä kasvatettiin, ja betonin lujuus jopa kasvoi karkean kierrätyskiviaineksen (RA) lisäämisen myötä huolellisen seossuunnittelun ansiosta. Kuitenkin kestävyysominaisuudet heikkenivät noin 20 % teollisessa mittakaavassa tuotettaessa, ja tämä heikkeneminen oli suurempaa silloin, kun karkeaa kierrätyskiviainesta käytettiin. MCDM-analyysin tulokset korostivat myös karkean kierrätyskiviaineksen (RA) alhaisempia kustannuksia, mikä tekee sen käytöstä suositeltavaa suurina betonimäärinä valettavissa SCC-komponenteissa. Kokonaisuudessaan karkean kierrätyskiviaineksen käytön lisäämistä esivalmistetun betonin teollisuudessa suositellaan ympäristöystävällisemmän rakennusalan edistämiseksi.

- **Rockwool waste in fly ash geopolymer composites/ Paivo Kinnunen, Juho Yliniemi, Bob Talling, Mirja Illikainen**

  https://oulurepo.oulu.fi/bitstream/handle/10024/24084/nbnfi-fe2019110436537.pdf?sequence=1&isAllowed=y

  Mineral wool waste is often considered unrecyclable, due to its difficult-to-process physical composition, and potential microbial contamination in the post-consumer products. Total mineral wool waste generated in the EU is growing continuously and is currently over 2.3 Mt annually, volumetrically accounting for the largest single waste source in some landfills. Here, we take advantage of the alkali-soluble nature of the rockwool waste and use a combined mixing and dissolution method to prepare this otherwise unusable waste for geopolymerization, with up to 33% inclusion in the final product. This mixing and dissolution step enables sufficiently high solids content to form a castable geopolymer paste, which forms a rigid matrix and a compressive strength of 12.8 MPa, sufficient for structural applications. This is the first time mineral wool waste has been used as a geopolymer precursor. FESEM and XRD analysis of the formed products were performed to verify geopolymer formation. By using the preparation reported here, otherwise unrecyclable mineral wool waste can potentially be turned into a valuable raw material for geopolymer materials.

  Kivivillajäte lentotuhka-geopolymeerikomposiiteissa/ Paivo Kinnunen, Juho Yliniemi, Bob Talling, Mirja Illikainen

Mineraalivillajätettä pidetään usein kierrätyskelvottomana sen vaikeasti käsiteltävän fyysisen koostumuksen ja kuluttajatuotteiden mahdollisen mikrobikontaminaation vuoksi. EU:ssa syntyvän mineraalivillajätteen kokonaismäärä kasvaa jatkuvasti ja on tällä hetkellä yli 2,3 miljoonaa tonnia vuodessa, mikä on tilavuudeltaan suurin yksittäinen jätelähde joillakin kaatopaikoilla. Tässä hyödynnämme kivivillajätteen alkaliliukoisuutta ja käytämme yhdistettyä sekoitus- ja liuotusmenetelmää valmistaaksemme tämän muuten käyttökelvottoman jätteen geopolymerointia varten, jolloin lopputuotteeseen lisätään jopa 33 % kivivillaa. Tämä sekoitus- ja liuotusvaihe mahdollistaa riittävän korkean kiintoainepitoisuuden valettavan geopolymeeripastan muodostamiseksi, joka muodostaa jäykän matriisin ja jonka puristuslujuus on 12,8 MPa, mikä riittää rakenteellisiin sovelluksiin. Tämä on ensimmäinen kerta, kun mineraalivillajätettä on käytetty geopolymeerin esiasteena. Muodostuneiden tuotteiden FESEM- ja XRD-analyysit suoritettiin geopolymeerien muodostumisen varmistamiseksi. Tässä raportoitua valmistustapaa käyttämällä muuten kierrätyskelvoton mineraalivillajäte voidaan mahdollisesti muuttaa arvokkaaksi raaka-aineeksi geopolymeerimateriaaleille.

- **Performance of steel-fiber-reinforced high performance one-part geopolymer concrete/ Zahra Abdollahnejad, Tero Luukkonen, Paivo Kinnunen, Mirja Illikainen**

  https://oulurepo.oulu.fi/bitstream/handle/10024/23121/nbnfi-fe201804126502.pdf?sequence=1&isAllowed=y

  The high CO2 emissions of Ordinary Portland Cement (OPC) production have led to increasing the efforts on developing eco-efficient alternative binders. Geopolymers are inorganic binders proposed as an alternative to OPC, which are mainly based on aluminosilicate by-products and alkali activators. Higher utilization of industrial waste materials, such as ceramic manufacturing waste, could be enabled by geopolymers. In ceramic industry, around 30% of raw materials end up in waste streams, and therefore, an attempt is made to recycle these materials. The ceramic wastes are rich in silicate and aluminate and have therefore high potential to be used in the geopolymeric concrete. In the present paper, the porcelain ceramic waste was used as 10% of total binder weight in substituting ground granulated blast furnace slag (GGBFS). The results showed that the resulting binders have comparatively high compressive strength (≥60 MPa), and show brittle behavior, which is typical to inorganic binders with no fiber reinforcement. Micro steel fibers were used to improve the flexural performance of these binders at three different fibers by mass of binder (0.5%, 1%, and 1.5%). After curing, mechanical performances were investigated by measuring the compressive and flexural strength. The results showed that the addition of steel fibers significantly improved the flexural behavior. In addition, it was revealed that these fiber-reinforced binders had a deflection hardening behavior due to the bridging action of steel fibers.

Teräskuiduilla vahvistetun korkean suorituskyvyn yksikomponenttisen geopolymeeribetonin suorituskyky/ Zahra Abdollahnejad, Tero Luukkonen, Paivo Kinnunen, Mirja Illikainen

Tavallisen portlandsementin (OPC) tuotannon korkeat hiilidioksidipäästöt ovat johtaneet lisääntyneisiin ponnisteluihin ympäristötehokkaiden vaihtoehtoisten sideaineiden kehittämiseksi. Geopolymeerit ovat epäorgaanisia sideaineita, joita on ehdotettu OPC:n vaihtoehdoksi ja jotka perustuvat pääasiassa alumiinisilikaattien sivutuotteisiin ja alkaliaktivaattoreihin. Geopolymeerit voisivat mahdollistaa teollisuusjätteiden, kuten keraamisen valmistusjätteen, tehokkaamman hyödyntämisen. Keramiikkateollisuudessa noin 30 % raaka-aineista päätyy jätevirtoihin, ja siksi näitä materiaaleja pyritään kierrättämään. Keraamiset jätteet ovat runsaasti silikaattia ja aluminaattia sisältäviä, ja niillä on siksi suuri potentiaali käyttää niitä geopolymeeribetonissa. Tässä artikkelissa posliinikeramiikkajätettä käytettiin 10 %:na sideaineen kokonaispainosta jauhetun rakeistetun masuunikuonan (GGBFS) korvaajana. Tulokset osoittivat, että saaduilla sideaineilla on suhteellisen korkea puristuslujuus (≥60 MPa) ja ne osoittavat haurautta, joka on tyypillistä epäorgaanisille sideaineille ilman kuitulujitetta. Mikroteräskuituja käytettiin näiden sideaineiden taivutusominaisuuksien parantamiseen kolmella eri sideaineen massapitoisuudella (0,5 %, 1 % ja 1,5 %). Kovettumisen jälkeen mekaanisia ominaisuuksia tutkittiin mittaamalla puristus- ja taivutuslujuus. Tulokset osoittivat, että teräskuitujen lisääminen paransi merkittävästi taivutuskäyttäytymistä. Lisäksi havaittiin, että näillä kuituvahvisteisilla sideaineilla oli taipumakarkenemiskäyttäytyminen teräskuitujen silloittavan vaikutuksen ansiosta.

- **Mineral wool waste-based geopolymers/ Juho Yliniemi, Tero Luukkonen, Anne Kaiser, Mirja Illikainen**

  https://oulurepo.oulu.fi/bitstream/handle/10024/23999/nbnfi-fe2019092730121.pdf?sequence=1&isAllowed=y

  Mineral wools –a general term for stone wool and glass wool– are the most common building insulation materials in the world. The annual amount of mineral wool waste generated in Europe totaled 2.3 Mt in 2010 – including wastes from the mineral wool production and from the construction and demolition industry. Unfortunately, mineral wools are often considered unrecyclable due to their fibrous nature and low density. Thus, the utilisation of post-consumer mineral wool waste in different applications remains low. Mineral wools have a great potential as geopolymer precursors as they have suitable chemical and mineralogical compositions. As geopolymers can provide significant CO2 emission reductions compared to traditional Portland cement concretes, using mineral wool waste as geopolymer precursor would be an attractive utilisation path. Here, we show that mineral wool waste can be geopolymerised to form sustainable cements with good mechanical properties. Geopolymerisation of

mineral wool waste ther efore offers an attractive route for waste valorisation and production of low-CO2 cements.

Mineraalivillajätteestä valmistetut geopolymeerit/ Juho Yliniemi, Tero Luukkonen, Anne Kaiser, Mirja Illikainen

Mineraalivillat – yleisnimitys kivivillalle ja lasivillalle – ovat maailman yleisimpiä rakennuseristysmateriaaleja. Vuonna 2010 Euroopassa tuotettiin vuosittain 2,3 miljoonaa tonnia mineraalivillajätettä – mukaan lukien mineraalivillan tuotannosta sekä rakennus- ja purkuteollisuudesta peräisin olevat jätteet. Valitettavasti mineraalivillaa pidetään usein kierrätyskelvottomana sen kuitumaisuuden ja alhaisen tiheyden vuoksi. Siksi kuluttajilta kerätyn mineraalivillajätteen hyödyntäminen eri sovelluksissa on edelleen vähäistä. Mineraalivillalla on suuri potentiaali geopolymeerien lähtöaineina, koska niillä on sopiva kemiallinen ja mineraloginen koostumus. Koska geopolymeerit voivat vähentää merkittävästi hiilidioksidipäästöjä perinteisiin portlandsementtibetoneihin verrattuna, mineraalivillajätteen käyttö geopolymeerien lähtöaineena olisi houkutteleva hyödyntämisvaihtoehto. Tässä osoitamme, että mineraalivillajätettä voidaan geopolymeroida kestävien, mekaanisesti hyvien ominaisuuksien omaavien sementtien muodostamiseksi. Mineraalivillajätteen geopolymerointi tarjoaa siksi houkuttelevan tavan jätteen hyödyntämiseen ja vähähiilidioksidipäästöisten sementtien tuotantoon.

- **Recycling and reusing of waste concrete fines as granulated aggregates/ Kalle Kursula**

  https://oulurepo.oulu.fi/bitstream/handle/10024/48537/nbnfioulu-202403122159.pdf?sequence=1&isAllowed=y

  In recent years, a large amount of construction and demolition waste has been generated by many demolition and construction projects because of fast urbanization. There is therefore a growing need for the sustainable management of construction waste and its recycling. The fine fraction of construction waste is especially challenging to reuse, and the problem is that it is yet to be fully utilized. Current options for the recycling of recycled concrete fines are limited, and there is a lack of research related to this. Today, recycled concrete fines are typically dumped in landfill, which requires large areas and may cause environmental contamination through water and soil pollution. The recycling and utilization of recycled concrete fines could make a significant contribution to sustainable development and the environment. This thesis, examined the possibility of the utilization of the recycled concrete fines. The general aim was to produce artificial aggregates from different recycled concrete fines by granulation. The results of this thesis show that with suitable co-binders and curing methods, it is possible to produce artificial aggregates from recycled concrete fines that have comparable engineering properties as commercial lightweight aggregates. Most of the produced artificial aggregates can be

classified as lightweight aggregates according to the EN 13055-1 standard. It was observed that the strength of the produced aggregates was highly dependent on their reactivity, particle size, and the different co-binders and curing methods used. The lightweight concrete produced from these artificial aggregates showed almost similar strength to lightweight concrete produced from commercial lightweight aggregate.

Rakennusjätteiden hienoaineksen hyödyntäminen uusiomateriaalien valmistuksessa/ Kalle Kursula

Kaupungistuminen on johtanut viime vuosina moniin rakennus- ja purkuprojekteihin, joka on tuottanut valtavan määrän erilaista rakennus- ja purkujätettä. Näin ollen rakennus- ja purkujätteen kierrättämiselle ja ympäristöystävälliselle uudelleenkäytölle on kasvavaa kysyntää. Erityisesti betonijätteestä syntyvä hienoaines on haastavaa kierrättää ja ongelmana on, ettei sitä pystytä täysin hyödyntämään.

Nykyiset vaihtoehdot jätebetonijauheen kierrättämiselle ovat vähäiset ja tutkimusta sen hyödyntämisestä on tehty vähän. Yleensä jätebetonin hienoaine on viety kaatopaikalle, mikä vaatii suuria maapinta-aloja ja on ympäristölle haitallista sillä se saattaa saastuttaa maaperää ja luonnonvesiä. Näin ollen jätebetonijauheen hyödyntämisellä olisi suuria etuja kestävän kehityksen ja ympäristön kannalta.

Tässä väitöskirjassa tarkoituksena on tutkia jätebetonin hienoaineksen hyödyntämismahdollisuuksia. Erityinen tavoite oli tuottaa aggregaatteja erilaisista jätebetonijauheista rakeistusprosessin avulla.

Väitöskirjan tulokset osoittavat, että sopivien sideaineiden ja kovetusmenetelmien avulla on mahdollista tuottaa jätebetonijauheesta aggregaatteja, joilla on vertailukelpoiset ominaisuudet kaupallisen kevytsoran kanssa.

Suurin osa tuotetuista aggregaateista voidaan luokitella kevytsoraksi standardin EN 13055-1 mukaan. Tutkimuksessa havaittiin, että tuotettujen aggregaattien lujuus riippui suuresti käytetyn betonijauheen reaktiivisuudesta ja partikkelikoosta, sekä käytetystä sideaineesta ja kovetusmenetelmästä. Näillä aggregaateilla valmistettujen kevytbetonien lujuus oli vertailukelpoinen kaupallisella kevytsoralla valmistettuun betoniin.

- **Mineraalivillajätteen geopolymerisointi/ Tuomas Hirvijoki**

  https://oulurepo.oulu.fi/bitstream/handle/10024/11900/nbnfioulu-201805091624.pdf?sequence=1&isAllowed=y

  Diplomityön tavoitteena oli selvittää, kuinka hyvin mineraalivillajäte soveltuu geopolymeerien raaka-aineeksi. Mineraalivillajäte on hankalasti kierrätettävää jätemateriaalia, jonka uudelleenkäytöllä rakennus- ja purkujätteen ympäristökuormitusta saataisiin pienennettyä huomattavasti. Jätettä syntyy

Suomessa yli 20 000 tonnia vuosittain, tehden siitä merkittävän yhteiskunnallisen ongelman kiertotalouden näkökulmasta.

Mineraalivillajätenäytteet kerättiin eri aikakausilta peräisin olevasta rakennus- ja purkujätteestä. Esikäsittelynä mineraalivillat jauhettiin kuulamyllyllä sekä osassa koesarjoja villojen sisältämä orgaaninen sideaine poistettiin kuumentamalla. Jauhetut mineraalivillat alkaliaktivoitiin eli geopolymerisoitiin kaliumsilikaattiliuoksella. Näytteet kovetettiin huoneenlämmössä tai ensimmäiset 24 tuntia 50°C:ssa ja sen jälkeen huoneenlämmössä. Valmistetuista geopolymeereistä määritettiin puristus- ja taivutuslujuuden kehitys ajan funktiona, veden absorptio, kestävyys jäätymis-sulamissyklejä vastaan ja niille suoritettiin röntgendiffraktioanalyysi.

Kaikki mineraalivillajätteet soveltuivat geopolymeerien lähtöaineeksi erinomaisesti. Työssä saavutettiin parhaimmillaan 60–65 MPa:n puristuslujuuden omaavia kivivillapohjaisia geopolymeerejä. Lasivillapohjaisille geopolymeereille mitattiin 60–70 MPa:n lujuisia puristuslujuuksia. Molempien villojen seokselle saavutettiin 30 MPa puristuslujuus.

Jäätymis-sulamissyklien jälkeen kivivillageopolymeerit säilyttivät lujuusominaisuutensa erinomaisesti. 116 syklin jälkeen kivivillageopolymeereillä oli yhä noin 45–60 MPa:n puristuslujuus, joka on tavallista betonia lujempi (42 MPa). Lasivillapohjaiset geopolymeerit eivät kestäneet jäätymis-sulamissyklejä yhtä pitkälle, joten ne eivät sovellu sellaisenaan ulkokäyttöön. Molempien villojen seoksesta valmistettu geopolymeeri kesti jäätymis-sulamissyklejä hyvin. Röntgendiffraktioanalyysi osoitti, että muodostuneet sidefaasit olivat täysin amorfisia, lukuun ottamatta muutamaa lasivillageopolymeeriä.

Työssä osoitettiin mineraalivillajätegeopolymeerien olevan potentiaalisia materiaaleja laastien ja betonien korvikkeeksi tulevaisuudessa. Tämä diplomityö luo pohjan jatkokehitykselle ja on todennäköistä, että tulevaisuudessa mineraalivillajätegeopolymeerejä voidaan käyttää monissa eri käyttötarkoituksissa.

Geopolymerization of mineral wool waste/ Tuomas Hirvijoki

The purpose of the thesis is to investigate whether mineral wool waste would be a suitable raw material for geopolymers. Mineral wool waste is difficult to recycle and finding new purposes for its use would reduce the carbon footprint of construction industry on environment. In Finland alone, over 20 000 tonnes of the waste is generated annually, posing a serious challenge for the circular economy of the country.

In this work, mineral wool waste was separated from construction and demolition waste from different time periods. As pre-treatment mineral wool wastes were milled with a ball mill and for certain experimental series the organic binder in mineral wool was removed by heating process. Milled mineral wools were alkali-activated i.e. geopolymerized with potassium silicate solution. Geopolymer samples were cured at room temperature or first 24h at 50°C and then at room temperature. Following

analyses were conducted for hardened geopolymer samples: development of compressive and flexural strength as a function of time, water absorption, resistance against freezethaw-cycles, and X-ray diffraction analysis.

All mineral wools were excellent raw material for geopolymers. At best stone wools geopolymers had 60-65 MPa compressive strength. Glass wool-based geopolymers had compressive strengths up to 60-70 MPa while the mix of both wools had compressive strength of 30 MPa.

Stone wool-based geopolymers had excellent resistance against freeze-thaw-process. It was determined that after 116 cycles stone wool-based geopolymers had still compressive strength of 45-60 MPa with no visible micro cracks. Glass wool-based geopolymers did not have as good freeze-thaw-resistance so they are not suitable for outdoor use as such. However, the mixes of both wools resisted freeze-thaw-process. Based on X-ray diffraction analysis the formed binding phases were amorphous.

The overall results found in this thesis indicate that geopolymers based on mineral wool waste could serve as a potential substitute for mortars and concretes. Hence, it is likely that mineral wool waste could serve as a raw material for construction industry in near future.

- **Investigation of the immobilization efficiency of toxic metals, and anions (Cl^-, F^-, SO_4^{2-}) from incineration ash in cementitious and alkali-activated systems/ Suman Kumar Adhikary, Nikhil Rathod, Tero Luukkonen, Priyadharshini Perumal. (2026) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2026.145309

  Ashes containing toxic metals, salts, or organic pollutants have strict environmental regulations for their safe disposal and reuse. In this study, fly ash and bottom ash from a solid recovered fuel and wood co-combustion power plant were used in alkali-activated blast furnace slag and Portland composite cement mortars to evaluate their mechanical and microstructural properties, as well as toxic metal leaching. The optimized alkali-activated mortar containing fly ash, bottom ash, and blast furnace slag in a ratio of 3: 7: 4 exhibited a 22 % increase in compressive strength compared with the slag-only reference mixture (0: 5: 2). In contrast, the cement mortar incorporating fly ash with a ratio of 1: 2.3: 1.7 (fly ash: bottom ash: CEM II) showed a 14 % reduction in compressive strength relative to the control sample (0: 2: 1). Leaching tests of raw fly ash showed that Cr, Mo, Pb, chloride (Cl^-), and sulfate (SO_4^{2-}) exceeded the Finnish leaching limits for earth construction, whereas raw bottom ash exceeded only the limit for antimony (Sb). When the ashes were alkali activated, the leaching of Cr, Mo, and Pb were significantly reduced compared to raw ashes, although Mo and fluoride (F^-) still exceeded the regulatory limits. Also in

cement mortars, a notable reduction in metal leaching was observed compared to raw ashes; however, the mortars containing higher fly ash showed increased leaching of As, Mo, Cl^-, SO_4^{2-}, and F^- over the sample without fly ash. This study provides an overall perspective on the reuse of co-combustion ashes in Portland-cement-based systems and alkali-activated binder systems, showing that the Portland-cement-based systems can effectively stabilize toxic metals and meet legislative limits with bottom ash. In contrast, both systems face challenges with fly ash in meeting the leaching requirements.

- **Synthesis and hydration mechanism of a steel-making by-product based quaternary binder suitable for superfine tailings/ Faguang Yang Adeolu Adediran, Chuqing Jiang, Yangmei Yu, Prince Allah, Chao Lyu2, Xiaoyu Li, Tuan Van Truong, Julson aymard Tchio, Nikhil Rathod, Priyadharshini Perumal. (2026) Journal of the American Ceramic Society**

  DOI: 10.1111/jace.70469

  The high cost and carbon emissions associated with traditional ordinary Portland cement (OPC) coupled with the poor consolidation of superfine tailings (ST) have become serious problems in the cemented superfine tailings backfill (CSTB). To avert this, using industrial by-products as a low-carbon, low-cost alternative binder to OPC is regarded as a promising solution. In this study, a novel steel-making by-product based quaternary binder (SQB) was developed using ladle slag (LS), calcium hydroxide (CH), dihydrate gypsum (DG), and ground granulated blast furnace slag (GGBFS) based on orthogonal protocols. The fresh and hardened properties of the CSTBs were evaluated at different SQB proportions, and the optimal ratio of SQB was determined using the TOPSIS method. The hydration mechanism and microstructural evolution of SQB were further systematically investigated using isothermal calorimetry analysis (ICA), x-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), thermogravimetry and differential thermogravimetry (TG−DTG), and scanning electron microscope (SEM). The results indicated that the proportion of each component in the SQB significantly affected the rheological properties of fresh CSTB slurries. Afterward, the optimal proportion of SQB was determined to be LS:CH:DG:GGBFS = 20:5:15:60, and its uniaxial compressive strengths (UCS) at 1, 3, 7, and 28 days were 1.11, 2.82, 6.23, and 9.45 MPa, respectively, which met the requirements of mine backfill. Moreover, the quaternary SQB system demonstrates more pronounced advantages, with significantly superior performance across all curing stages compared to the corresponding ternary system (without CH). The hydration mechanism and microstructural development of SQB revealed a synergistic reaction between sulfate-activated LS and alkali–sulfate-activated GGBFS, resulting in the formation of a large amount of ettringite (AFt) and calcium silicate hydrate (C–S–H) gels and a denser microstructure. Overall, the

synthesized SQB offers an eco-friendly and economical alternative for CSTB, which has notable engineering application prospects.

- **Composition-properties-performance relationships of alkali-activated materials and geopolymers over extended silicon-aluminum-sodium-calcium ratios in adsorption applications/ Md Faysal Hossain, Md Akram Hossain, Mohammad Bhuyan, Jouko Vepsäläinen, Tero Luukkonen. (2026) Materials and Design**

  DOI: 10.1016/j.matdes.2026.115471

  Composition of alkali-activated materials (AAMs) and geopolymers affects their material properties and performance in adsorption applications, yet their correlations remain largely unexplored. In this study, AAMs/geopolymers were synthesized by systematically varying their compositions in the ranges $Si_1Al_1Na_1$–$Si_{20}Al_1Na_1$ (i.e., Ca-free geopolymers) and $Si_1Al_1Na_1Ca_2$–$Si_{20}Al_1Na_1Ca_{21}$ (i.e., Ca-containing AAMs). The material properties (e.g., connectedness of the aluminosilicate structure, specific surface area, pore volume, average pore size and zeta potential) of AAMs/geopolymers were correlated with adsorption performance for cations with different aqueous radii: methylene blue (MB), rhodamine 6G (R6G), and ammonium (NH_4^+). In the Ca-free geopolymers, the adsorption of MB and R6G increased with increasing the Si/Al molar ratio and strongly correlated with specific surface area, whereas NH_4^+ adsorption showed an opposite trend, correlating positively with the Al/Si ratio and zeta potential but negatively with specific surface area. Adding Ca to the systems caused the adsorption amounts for MB, R6G, and NH_4^+ reaching a minimum at $Si_5Al_1Na_1Ca_6$ composition while lower or higher Ca content increased adsorption. The results of this study could be a valuable reference for tailoring the future AAM/geopolymer compositions over wide Si:Al:Na:Ca ratios to obtain specific material properties in high-end applications, such as wastewater treatment.

- **Mechanical properties, 3D printing and environmental performance of Ordinary Portland Cement (OPC) mortars containing calcite rich residue from stabilised basic oxygen furnace slag/ Patrick N. Lemougna, Marco Cantaluppi, Flora Faleschini, Klajdi Toska, Pekka Tanskanen, Juho Yliniemi, Katja Kilpimaa. (2026) Cleaner Engineering and Technology**

  DOI: 10.1016/j.clet.2026.101206

  The metallurgy industry generates slags, and their recycling is crucial for promoting a circular economy and addressing environmental management concerns. This study investigated the potential for upcycling a calcite-rich stream, derived from vanadium recovery from Basic Oxygen Furnace (BOF) slag, as a Supplementary Cementitious

Material (SCM) in concrete. Blended pastes and mortars were prepared by partially replacing cement with the residue. The effects of cement substitution were evaluated using isothermal calorimetry, rheology and consistency tests, X-ray diffraction (XRD), and Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS). The results showed that the residue consisted mainly of calcite and aragonite, with a randomly shaped morphology and a median particle size of around 2 µm. The residue exhibited moderate reactivity as a SCM, assessed by the Rapid, Relevant, Reliable (R3) test. After 28 days, the compressive strength of samples with up to 30% cement replacement satisfied the 75% strength activity index requirement. Environmental leaching tests conducted on the prepared mortars demonstrated significant immobilization of heavy metals from the residue within the concrete matrix. Preliminary 3D printing tests indicated that the residue enhanced printability by reducing concrete segregation, due to its finer particles. These results highlight the potential for valorising calcium-rich side streams and similar waste materials, contributing to improved circular economy practices and reduced environmental impact in both the metallurgy and construction industries.

- **Properties of Fe-bearing Mg silicate glasses as novel supplementary cementitious materials/Jiang, Hellen, Silva Santos, Labeed Ahmad, Juho Yliniemi, Christopher Cheeseman, Paivo Kinnunen. (2026) Chemical Engineering Science**

  DOI: 10.1016/j.ces.2026.123472

  Blended cements incorporating supplementary cementitious materials (SCMs) offer a viable strategy for reducing the carbon footprint of Portland cement. As traditional SCMs (e.g., blast furnace slags, coal fly ash) become increasingly scarce, the development of alternative materials is crucial. This study evaluates synthetic Fe-bearing Mg silicate glasses as potential low-carbon SCMs, free from direct CO_2 emissions associated with raw material processing. Three types of synthetic glasses (Mg-Si, Fe^{3+}-Mg-Si, and Fe^{2+}/Fe^{3+}-Mg-Si glasses) were assessed for their pozzolanic activity and used to replace 20 wt% of Portland cement. Mortar samples incorporating these glasses demonstrated a strength activity index increase of up to 120% compared to the control. Microstructural analysis revealed enhanced formation of C-(A-)S-H and Fe-bearing Mg-containing phases, including Mg-Al(Fe) layered double hydroxides (LDHs). The incorporation of Fe was observed to promote Al mobilization, facilitating early sulfate reactions and potentially influencing cement hydration kinetics. This work shows how non-conventional glass-based SCMs can be engineered to enhance blended cement performance while lowering carbon emissions.

- **Cleaner utilization of co-combustion bottom ash in concrete: Pilot-scale validation for sustainable construction/ Suman Kumar Adhikary, Teemu Turpeinen, Anshumali Mishra, Nikhil Rathod, Adeolu Adediran, Tero Luukkonen, Priyadharshini Perumal. (2026) Resources, Conservation and Recycling Advances**

  DOI: 10.1016/j.rcradv.2025.200311

  The co-combustion of biomass and solid recovered fuel generates substantial quantities of bottom ash (BA), and safe value-added utilization in construction remains insufficiently explored. This study evaluates the feasibility of using co-combustion bottom ash (CCBA) as a fine aggregate replacement in concrete through comprehensive mechanical, durability, and environmental assessments supported by pilot-scale validation. Concrete mixtures with 0 %, 50 %, and 100 % CCBA were studied as replacement of natural sand. Incorporating CCBA improved mechanical performance, with a maximum 10.48 % increase in 28-day compressive strength of concrete compared to the natural-sand reference. Durability assessment demonstrated excellent resistance to sulfuric acid (5 % sulfuric acid solution immersion) with only a 9.7 % strength loss at 100 % BA replacement, and strength gains of up to 21.3 % after sulfate-chloride exposure. Concrete samples also showed strong freeze-thaw resistance, reduced sorptivity with BA content, and improved microstructural densification supported by EIS analysis. Leaching tests confirmed effective immobilization of toxic metals within the cementitious matrix, meeting Finnish environmental regulations without ash pre-treatment. Pilot-scale production of 10 tons of concrete barrier blocks further validated the field performance, showing no visible damage after exposure to harsh Nordic climatic conditions. The results demonstrate that CCBA is a technically viable, environmentally safe, and sustainable alternative to natural sand for large-scale concrete production.

- **Mineralogical Transformations of H2-DRI-EAF Slag by Carbonation Treatment Improves the Performance of the Slag as Supplementary Cementitious Material/ Srujana Gouda, Hoang Nguyen, Vitalii Ponomar, Elijah Adesanya, Juho Yliniemi, Katja Kilpimaa. (2026) Journal of Sustainable Metallurgy**

  DOI: 10.1007/s40831-026-01409-y

  Steel slag is an emerging supplementary cementitious material (SCM) that can reduce the carbon footprint of cement. This study reports the use of an electric arc furnace (EAF) slag from new steelmaking process i.e. direct hydrogen-assisted iron reduction (i.e., H2-DRI-EAF route) as an SCM. Further analysis was conducted to examine the effects of carbonation methods including semi-dry and aqueous carbonation on the hydration of slag in blended cements. The results indicate that the

carbonation of the slag led to the formation of amorphous silica, crystalline and amorphous CaCO3 which contributed to the hydration reactions in blended cement. The pozzolanic activity and hydration behavior of carbonated slag were further assessed using R3 test and isothermal calorimetry while SEM–EDS, XRD, and TGA were used to analyze the phase transformations after carbonation. Between the two carbonation methods, the aqueous carbonation led to a higher CO2 uptake (9.5 g/100 g slag) and better reactivity. This is due to the formation of more reactive phases such as amorphous silica and calcium carbonates which linked to diverse hydration product formation such as C-(A)-S–H, AFt and hydrotalcite. The compressive strength showed an increase of 53 and 7% at 7 and 28 days of hydration in slag-blended samples compared to limestone-based blend. The findings reveal that the EAF slag from this novel steelmaking process is suitable for carbonation and utilization as SCM.

- **Properties of Fe-bearing Mg silicate glasses as novel supplementary cementitious materials/ Chuqing Jiang, Hellen Silva Santos, Labeed Ahmad, Juho Yliniemi, Christopher Cheeseman, Paivo K innunen. (2026) Materials Chemistry and Physics**

  DOI: 10.1016/j.matchemphys.2026.132072

  Blended cements incorporating supplementary cementitious materials (SCMs) offer a viable strategy for reducing the carbon footprint of Portland cement. As traditional SCMs (e.g., blast furnace slags, coal fly ash) become increasingly scarce, the development of alternative materials is crucial. This study evaluates synthetic Fe-bearing Mg silicate glasses as potential low-carbon SCMs, free from direct CO_2 emissions associated with raw material processing. Three types of synthetic glasses (Mg-Si, Fe^{3+}-Mg-Si, and Fe^{2+}/Fe^{3+}-Mg-Si glasses) were assessed for their pozzolanic activity and used to replace 20 wt% of Portland cement. Mortar samples incorporating these glasses demonstrated a strength activity index increase of up to 120% compared to the control. Microstructural analysis revealed enhanced formation of C-(A-)S-H and Fe-bearing Mg-containing phases, including Mg-Al(Fe) layered double hydroxides (LDHs). The incorporation of Fe was observed to promote Al mobilization, facilitating early sulfate reactions and potentially influencing cement hydration kinetics. This work shows how non-conventional glass-based SCMs can be engineered to enhance blended cement performance while lowering carbon emissions.

- **Polycarboxylate ether as a grinding aid for basic oxygen furnace slag and its effects in blended cements/ Milad Eskandarinia, Elijah Adesanya, Brant Walkley, Juho Yliniemi. (2026) Journal of Building Engineering**

  DOI: 10.1016/j.jobe.2026.115331

  This research investigates polycarboxylate ether (PCE) as a grinding aid to enhance the grinding efficiency and cementitious properties of basic oxygen furnace (BOF) slag in cement applications. Ground BOF slag samples with and without PCE were systematically characterized using particle size analysis (wet and dry dispersion), Blaine fineness, BET surface area, scanning electron microscopy, FT4 powder rheometer, and surface energy by inverse gas chromatography (IGC) using a surface energy analyzer (SEA). Results indicated that a low dosage of PCE (0.05 %) significantly improved the grinding process by reducing the median particle size from 16.0 ± 0.2 μm to 13.8 ± 0.7 μm and increasing the Blaine surface area from 4149 ± 11 to 4514 ± 24 cm2/g compared to untreated ground BOF slag. This enhancement was attributed to the ability of PCE to minimize the agglomeration of particles while maintaining reasonable flow properties during grinding, even in the presence of high-energy surface sites associated with finer particles, as identified through IGC-SEA analysis. Conversely, overdosing PCE (0.5 %) led to excessive agglomeration, reflected by an increase in the agglomeration factor to 83, and together with poor powder flowability, ultimately reducing grinding efficiency. The hydration kinetics, rheological properties, and mechanical behavior of PCE-treated BOF slag-Portland Cement blends were investigated. BOF slag ground with a low dosage of PCE slightly enhanced the hydration process of the blended system, ultimately resulting in higher 28-day compressive strength (42.3 ± 0.2 MPa) compared to untreated ground BOF slag (39.3 ± 0.6 MPa). While partial replacement of cement with BOF slag positively impacted the rheological properties of the blended systems, BOF slag treated with a high dosage of PCE led to a pronounced reduction in viscosity (6.2 ± 0.1 Pa·s) and yield stress (46.2 ± 2.5 Pa) of the system. These findings demonstrate the potential of PCE as a dual-function admixture for improving both slag grinding and blended cement performance.

- **Competitive complexation mechanisms between Ca, Al, Fe, Mg, Si and triisopropanolamine (TIPA) at pH 13/ Xiaowen Zhang a , Otto Mankinen b , Juho Yliniemi (2026) Cement and Concrete Research**

  DOI: 10.1016/j.cemconres.2026.108194

  Triisopropanolamine (TIPA) can affect reactivity and hydration process of clinker phases and supplementary cementitious materials by forming aqueous complexes with the elements in the pore solution, yet competitive complexation mechanisms

remain uncharacterized at the molecular level. This study establishes TIPA's competitive binding with five elements (Ca, Al, Fe, Mg, Si) at pH 13 through 1H NMR spectroscopy, ESI-MS spectrometry, and ICP-OES analysis. Single-metal systems reveal a binding hierarchy where Al and Fe form kinetically stable complexes with distinct stoichiometries, while Ca and Mg exhibit weak binding. TIPA provides the sole Fe solubilization pathway (510-fold enhancement), whereas Al maintains alternative solubility through $Al(OH)_4^-$ formation. Multi-metal competition produces four element-selective, non-cumulative effects: mutual reduction in Ca + Al systems; synergistic enhancement in Ca + Al + Fe systems; selective Mg antagonism disrupting Fe-TIPA while preserving Al-TIPA coordination; Si-triggered co-precipitation removing Ca and Al while Fe-TIPA remains stable. These phenomena arise from parallel equilibria rather than sequential displacement, explaining TIPA's unpredictable performance. These mechanisms enable rational admixture optimization in chemically diverse cementitious systems.

- **Quarry waste clays as supplementary cementitious materials: Mineralogical evolution and pozzolanic performance after thermal activation/ Erdi Avci, Elif Sidimi, Nana Asaam, Aysu Dag, Atiye Tugrul, Priyadharshini Perumal. (2026) Applied Clay Science**

  DOI: 10.1016/j.clay.2025.108085

  This study investigates the potential of thermally activated quarry waste as alternative supplementary cementitious materials (SCMs) for sustainable binder systems. Three clay-rich materials were collected from a sand quarry located on the European side of Istanbul: two natural overburden clays (Yellow Layer-YL and Blue Layer-BL) and one process-derived sludge waste (TA) generated during sand washing. All samples were sieved (<150 μm), dried, and calcined at 800 °C for 2 h. Mineralogical (XRD), chemical (XRF), and thermal (TG, FTIR) analyses were conducted to evaluate phase transformation and amorphous phase development. Pozzolanic reactivity was assessed by the R3 test, including heat release and bound water measurements. Results showed that the TA sample exhibited the highest reactivity due to its kaolinite content and fine, homogeneous particle structure. In contrast, the BL sample demonstrated limited reactivity owing to the dominance of thermally stable phases such as muscovite and albite. Mortar specimens prepared with 20 % SCM replacement were tested for compressive strength at 7, 14, and 28 days using both CEM I and CEM II binders. The TA-C mixture achieved a compressive strength index (CSI) of 102.9 % with CEM I at 14 days, indicating strong early-age performance, while YL-C showed the highest 28-day strength with CEM II (CSI = 97.9 %). These findings confirm that sludge-based SCMs, when properly activated, can match or even exceed the performance of conventional systems, offering a viable strategy for resource-efficient and low-carbon cementitious materials.

- **Low-Carbon Composite Cement Mortar Incorporating Local Raw Materials as SCMs: Performance and Life Cycle Analysis/ Adeolu Adediran, Nana Asaam, Javier Manso-Morato, Priyadharshini Perumal. (2026) Journal of the American Ceramic Society**

  DOI: 10.1111/jace.70717

  Performance and life cycle analysis of composite cement mortars developed using local conventional (blast furnace slag and fly ash) and novel non-conventional (stone wool, glass wool, calcined Finnish clay, volcanic pozzolan Iceland, and ladle slag) raw materials as supplementary cementitious materials (SCMs) was investigated. The SCMs and the prepared mortars were characterized using x-ray diffraction, FTIR, TG-DTG, SEM-EDS, flowability, compressive strength, ultrasonic pulse velocity (UPV), water absorption, permeable porosity, and life cycle analysis (LCA). Experimental results showed a difference in the physical, chemical, and mineralogical composition of the SCMs, which in turn influenced the properties of the composite cement mortars developed. Ladle slag (30 wt.%) as SCM performed better, resulting in mortars with comparable mechanical, UPV, water absorption, permeable porosity, and microstructural properties but lower flowability values compared with reference mortars. In contrast, the use of other SCMs resulted in mortars with slightly lower mechanical properties, increased workability, and higher water absorption and permeable porosity than the reference mortars. The better performance of ladle slag may be attributed to the increased amount of precipitated hydration phases and formation of supplemental pore-filling hydration products, such as C_3AH_6 and $Al(OH)_3$, attributed to the dissolution and participation of alumina from the SCM in gel formation. LCA results revealed a reduction in the environmental impact of the composite cement mortars (except those containing Finnish clay as SCM) when compared to PC-based mortars.

- **New Insight into the Reactivity of Steel Slags: Effect of Post-milling Duration/ Milad Eskandarinia, Elijah Adesanya, Brant Walkley, Juho Yliniemi. (2026) Journal of Sustainable Metallurgy**

  DOI: 10.1007/s40831-026-01421-2

  Incorporating steel slag, a residue derived from the metallurgical industry, into cementitious systems offers a sustainable route for resource recovery and carbon footprint reduction. Milling has been reported to address the low cementitious reactivity of steel slag, which remains a significant barrier to its widespread adoption. However, the influence of storage duration after milling on steel slag performance has not been systematically evaluated. To investigate the effects of post-milling duration as an independent factor, two types of steel slag, derived from a basic

oxygen furnace and an electric arc furnace processes, were milled using planetary ball milling and stored under controlled environmental conditions for 1 h, 1 day, 4 days, 7 days, 3 months, and 1 year. The results showed that prolonged storage caused significant particle agglomeration, detected by particle size analysis, and a slight reduction in reactivity after 1 year, as determined by the Rapid, Reliable Relevant (R3) reactivity test for supplementary cementitious materials. Replacing 30% of cement with steel slags stored for different times (1 h vs. 1 year) changed the properties of the blends. Compared with freshly milled slag, slag stored for 1 year caused a slight delay in cement hydration, as evidenced by calorimetry results. Consequently, blends containing 1-year-stored slag exhibited prolonged setting times and reduced apparent viscosity compared with the 1-h slag–cement blends. The compressive strength of blended cements was also negatively affected by long-term storage, and the amount of hydration products, such as portlandite, was slightly reduced in 28-day composites containing 1-year-stored slag.

- **Combined Role of Organic Ligands and Ultrasound on the Dissolution of Phlogopite at pH 4 and 7/ Mahtab Akbarzadeh Khoei, Recep Kurtulus, Mohammad I. M. Alzeer, Juho Antti Sirviö, Juho Yliniemi. (2025) Langmuir**

  DOI: 10.1021/acs.langmuir.4c04307

  Phlogopite, a mineral produced in large quantities by the mining industry, has potential applications in the cement industry, fertilizers, and carbon storage, but its use is limited by the slow dissolution caused by its stable crystalline structure. This study investigated the combined effect of ultrasound waves and organic ligands (citrate, oxalate, and ethylenediamine) on the extraction of elements from phlogopite at acidic and neutral pH using batch dissolution experiments. It was hypothesized that sonicated samples would exhibit improved dissolution compared to mechanically stirred samples. The results showed that the dissolution of phlogopite increases in sonicated samples in the presence of an organic ligand. This enhancement depends on ligand type, with the effect being notably higher in the case of the sample containing citrate. In addition, pH plays an important role, as element extraction percentages were significantly higher at an initial pH of 4 compared to pH 7. The surface study suggests that ultrasound waves affect the morphology of phlogopite; however, there is no noticeable effect on preventing the reaccumulation of elements on the surface. The findings suggest that sonication, along with organic ligands, could be a useful processing step for the utilization of phlogopite in different applications. This research provides novel insights into the complex dynamics of enhanced dissolution and the interfacial interactions involving sonication and organic ligands.

- **Concentrated salt water can partially replace sodium hydroxide in alkali activation of blast furnace slag/ Sima Kamali, Minna Patanen, Juho Yliniemi, Katja Kilpimaa, Tero Luukkonen. (2025) Journal of the American Ceramic Society**

  DOI: 10.1111/jace.20596

  Alkali-activated materials are low-CO_2 alternative binders, but the alkali-activator component contributes significantly to the CO_2 emissions, costs, and safety risks. This study explores the potential of partially replacing NaOH with highly concentrated salt waters as an activator for blast furnace slag and related chemical mechanisms. Four water types were compared: simulated brine (~105‰ salinity), NaCl and Na_2SO_4 solutions, and deionized water. Results show that NaOH molarity can be reduced to 0.1 mol/L (or 0.16 weight% NaOH of slag weight—a significantly lower value than typically required) using simulated brine, while achieving a 28-day compressive strength of 28.0 MPa—more than double compared to deionized water. Slag dissolution increased substantially upon using salt waters with 0.1 mol/L NaOH in comparison to deionized water. Thermodynamic modeling and slag dissolution studies indicated that salt anions (e.g., SO_4^{2-} and Cl^-) formed ion-pair complexes with Ca and Mg, and thus drove the enhanced slag dissolution. The similar likely occurs also when using Na_2SO_4 as an alkali activator for which the mechanism has been unclear in the existing literature. From the practical point of view, the highly concentrated salt waters could largely replace NaOH in certain applications of alkali-activated slags when no steel reinforcements are required.

- **Ammonium recovery from wastewater by ion exchange using porous metakaolin geopolymer granules over extended adsorption/ regeneration cycles/ Yangmei Yu, Mohammad Bhuyan, Priyadharshini Perumal, Tero Luukkonen. (2025) Applied Surface Science Advances**

  DOI: 10.1016/j.apsadv.2025.100910

  Ion exchange on porous geopolymer granules represents a potentially promising unit process for ammonium (NH4+) recovery from wastewater. However, the previous studies have not systematically optimized the regeneration nor evaluated the robustness of the ammonium recovery over extended adsorption/regeneration cycles. In this study, NaCl, Na2SO4, NaNO3, KNO3, K2SO4, CH3COOH, and combined NaOH/NaCl at concentrations of 0.3–0.9 M and thermal regeneration at 500 °C were compared for the regeneration of NH4+-saturated geopolymer granules. 0.9 M KNO3 exhibited the best performance. The adsorption/regeneration cycles were repeated 30 times in synthetic wastewater and 5 times in tertiary municipal wastewater (directly or after filtration with 0.45 μm membrane). The porous

geopolymer granules (size 2–4 mm) had an average NH4+ ion exchange capacity of 9.0 mg/g and NH4+ recovery of 51–98 % over the 30 adsorption/regeneration cycles in synthetic wastewater (initial concentration 500 mg/L). After 20 cycles, the ion exchange capacity of the granules started to decrease. The characterization of the granules after 30 cycles indicated that a minor amount of µm-sized particles were disintegrated from their surface and 70 % of the Al sites were no longer converted into K-form during regeneration. In municipal wastewater, the NH4+ uptake was 3.9 mg/g on average (initial concentration of 67 mg/L). The NH4+ recovery was 68 % and 74 % during the 5th cycle in raw tertiary wastewater and filtrated wastewater, respectively. Wastewater caused pore blocking and accumulation of solids on the surface which were reduced by the filtration. This study highlights the importance of the pretreatment before applying geopolymers for NH4+ recovery in realistic conditions and that the porous geopolymer granules have a lifetime of 20 adsorption/regeneration cycles before their ion exchange capacity begins to decline.

- **Dissolution and surface study of phlogopite in the presence of ethylenediamine at pH 4–13/ Mahtab Akbarzadeh Khoei, Mohammad I.M. Alzeer, Juho Yliniemi. (2025) Applied Surface Science**

  DOI: 10.1016/j.apsusc.2024.161178

  Phyllosilicate minerals are relevant in several environmental applications, such as supplementary cementitious materials, carbon capture and storage, and nuclear waste disposal. Therefore, it is important to understand how phyllosilicates react with aqueous solutions and the components within the solutions. In this study, the interaction between ethylenediamine and the surface of milled phlogopite was investigated within a pH range of 4–13. X-ray diffraction analysis of raw and milled phlogopite sample was conducted prior to the experiments. Solution compositions after batch titration experiments were determined using inductively coupled plasma optical emission spectrometry, and the remaining phlogopite was analyzed using X-ray photoelectron spectroscopy, Fourier transform infrared spectroscopy, zeta potential, and thermogravimetry/differential thermal analysis. The results indicate that the combined effect of HNO3—used to control the pH—and the presence of ethylenediamine improves phlogopite dissolution at pH 4. Conversely, the maximum accumulation of ethylenediamine at pH 7 inhibits the dissolution and blocks the phlogopite surface. At pH 10 and 13, ethylenediamine exhibits predominantly neutral and negative charges, respectively. This charge distribution indicates a lack of significant interaction with the negatively charged phlogopite surface, however despite that, ethylenediamine accumulated Al, Mg, and Fe on the surface.

- **Adsorption properties of alkali-activated stone wool/ Cansu Kurtulus, Tero Luukkonen. (2025) Ceramics International**

  DOI: 10.1016/j.ceramint.2024.11.126

  Alkali-activated materials are actively studied as adsorbents for toxic metals, nutrients, and dyes from wastewater. They are produced using an environmentally friendly process from low-cost aluminosilicate precursors, and thus have significant potential for fostering the development of clean technology. One of the potential precursors is stone and glass wool, for which alkali activation has been successfully demonstrated in construction products. In this study, alkali-activated stone wool was assessed for adsorption for the first time. Stone wool manufactured without organic resin (SW) and another stone wool with organic resin being removed by heat treatment (SW-O) were alkali activated using NaOH, Na_2CO_3, $NaAlO_2$, or Na silicate solution, and characterized by X-ray diffraction, scanning electron microscopy, Fourier-transform infrared spectroscopy, thermogravimetry–mass spectrometry, and potentiometric titrations to understand the surface properties affecting adsorption. Comparative adsorption experiments were conducted using methylene blue (MB), cobalt (Co(II)), arsenite (As(III)), and NH_4^+ at 100 mg × L^{-1} concentration, 1 g × L^{-1} adsorbent dose, 24 h contact time, and pH of 7. The raw stone wools demonstrated almost no adsorption, whereas the alkali-activated stone wools adsorbed up to 78, 42, 3, and 18 mg × g^{-1} of MB, Co(II), As(III), and NH_4^+, respectively. The samples prepared with the SW Na silicate demonstrated higher adsorption capacities for MB and Co(II). For As(III), an adsorption capacity was similar regardless of the mixture. The highest adsorption capacity for NH_4^+ was achieved with SW-O NaOH. The increased adsorption capacities were related to the increase in the specific surface area, more negative zeta potential, formation of tobermorite-like structures, and an increase in the quantity of surface OH groups. The varying adsorption levels of specified contaminants are possibly governed by their speciation at pH 7, aqueous radii, and the adsorption mechanism. This study demonstrated that stone wool-based adsorbents could have practically relevant potential for wastewater treatment.

- **The effect of gypsum on reaction kinetics and microstructure of alkali-activated CaO-FeOx-SiO2 slag/**
  Vitalii Ponomar, Sima Kamali, Tero Luukkonen, Ailar Hajimohammadi, Katja K ilpimaa. (2025) Cement and Concrete Composites

  DOI: 10.1016/j.cemconcomp.2025.106033

Gypsum is commonly used in conventional cement systems to regulate setting time and enhance early strength. However, its role in alkali-activated materials (AAMs) is less well understood due to the distinct chemistry of precursors and reaction products. This study investigates the impact of synthetic and industrial gypsum on the reaction kinetics and microstructure of CaO-FeO_x-SiO_2 slag activated with sodium silicate and sodium hydroxide, supported by dissolution-precipitation tests. Results demonstrate that gypsum addition to sodium silicate solution promotes the precipitation of C-S-H gel, which evolves into two distinct compositional varieties in the paste environment with slag, influencing the reaction kinetics. The early formation of Ca-rich gel accelerates the setting time but initially reduces the strength. The delayed formation of main Si-rich gel matrix leads to strength gain over time, with the 1 % industrial gypsum sample achieving 90 MPa at 28 days. In NaOH solutions, gypsum induces portlandite precipitation but the formation of a rod-like thaumasite phase ($CaSiO_3 \cdot CaCO_3 \cdot CaSO_4 \cdot 15H_2O$) in the slag paste environment. The early formation of sulphate phases improves early mechanical performance but compromises durability due to the expansive nature of thaumasite growth. These findings underscore the dual role of gypsum in controlling setting time and strength in AAMs and highlight the need to optimize gypsum type and content to address challenges posed by precursor chemistry.

- **Alkali-activated materials containing mine tailings and zeolite for seepage water treatment in a closed nickel mine/ J. Laukkanen, H. Runtti, I. Lancellotti, T. Luukkonen, C. Leonelli, U. Lassi. (2025) International Journal of Environmental Science and Technology**

  DOI: 10.1007/s13762-024-06002-y

  In the present study, alkali-activated materials were assessed as adsorbents for mine water treatment. The composition of alkali-activated materials, involving mixtures of metakaolin, blast-furnace slag, mine tailings, and zeolite, was optimized based on their leaching behavior and adsorption performance. The most effective adsorbent contained solely blast furnace slag as an aluminosilicate precursor and was selected for a pilot-scale study at a closed nickel mine in Finland. In the pilot, seepage water from a gangue area with an influent flow rate of 0.5 m3/d was treated using a permeable reactive barrier set-up containing 10 kg of slag-based adsorbent prepared by a granulation-alkali activation process. During a one-week experiment, the adsorbent granules were capable of effectively uptaking Ni, Fe, and Mn from the seepage water; the removal percentages of Ni, Fe, and Mn were 82.4%, 81.6%, and 82.5%, respectively. The results indicated the feasibility of blast furnace slag-based adsorbents for toxic element removal in a potentially sustainable approach.

- **Transition metal-modified alkali-activated aluminosilicate foams as catalysts for peracetic acid in phenol abatement/ Mehedi Rabbil, Mohammad Bhuyan, Mohammad Alzeer, Elijah Adesanya, Ter o Luukkonen. (2025) Ceramics International**

  DOI: 10.1016/j.ceramint.2025.04.065

  The use of peracetic acid (PAA, $CH_3C(O)OOH$) in advanced oxidation processes has recently attracted attention for the abatement of micropollutants. Radical formation from PAA can be activated by transition metals and to achieve sustained catalytic performance, one strategy is to immobilize the metals on a support. In this study, alkali-activated aluminosilicate foams (AAFs) synthesized from metakaolin, glass wool, stone wool, or blast furnace slag at 22 or 60 °C were compared as supports for Mn(II), Fe(III), Cu(II), and Co(II) either with or without calcination at 400 °C and tested for aqueous phenol abatement. The best precursor was metakaolin (MK) cured at 22 °C, showing a compressive strength of 0.67 MPa, ~82 % porosity, and stable pH after treatment with 0.1 M acetic acid. Among the four metals, Co(II)-modified MK-AAFs dried at 60 °C showed the best PAA activation performance due to high metal content (2.7 wt%), minimal leaching (0.09 %), and stable neutral pH. Flow-through column experiments using crushed Co(II)-modified MK-AAF pieces (20 g, 5.6–10 mm size) were investigated to assess the effects of empty bed contact time (15–25 min) and PAA dose (0.4–1.2 mM) on phenol (10 μM) abatement at a pH of 7.4. Under optimal conditions (1.2 mM PAA and 15 min contact time), up to ~97 % of phenol abatement was achieved. In a long-term experiment (180 bed volumes of treated water), the phenol abatement decreased from ~94 % to ~70 % after 120 bed volumes and remained stable after that. This study demonstrates that Co(II)-containing MK-based geopolymer foams could be an effective catalyst for developing PAA-based advanced oxidation processes.

- **Examining reproducible mix design, fresh and mechanical properties of ground granulated blast furnace slag-based alkali-activated concrete (GGBFS-based AAC): results of an interlaboratory study of RILEM TC 294-MPA/ Patricia Kara De Maeijer , Guang Ye, Zhenming Li, Kruthi Kiran Ramagiri, Geert De Schutter, Yubo Sun, Frank Dehn, Arkamitra Kar, Juho Yliniemi, Yuwei Ma, Kazuo Ichimiya, Giulia Masi, Quoc Tri Phung, Wei Sha. (2025) Materials and Structures/Materiaux et Constructions**

  DOI: 10.1617/s11527-025-02754-2

  This report presents a meticulous synthesis of collaborative interlaboratory research conducted within the purview of the RILEM Technical Committee 294-MPA, with two expert groups named RRT1 and RRT2, and encompassing ten participants from

Belgium, China, Finland, India, Italy, Japan, the Netherlands, and the United Kingdom. The RRT1 expert group mainly focused on the ground granulated blast furnace slag-based alkali-activated concrete (GGBFS-based AAC) mix design and mechanical properties. In turn, the RRT2 expert group focused on the fresh properties of GGBFS-based AAC. The investigation, conducted between 2020 and 2024, aimed to establish globally reproducible mix design and mixing protocols for GGBFS-based AAC. Developed by the RRT1 and RRT2 expert groups, these protocols have emerged through iterative experiments followed by a comprehensive interlaboratory study. The outcomes highlight the reliable production of GGBFS-based AAC across participants, with minor deviations in fresh and mechanical properties that are largely consistent with those observed in Portland cement concrete (PCC). The primary objective of the developed GGBFS-based AAC mix design was to achieve a defined consistence class S4, while targeting a compressive strength threshold of approximately 50 MPa at 28 days. This objective was effectively realized, with the average compressive strength values reaching 56 MPa at 28 days and 64 MPa at 720 days. While the average splitting tensile strength stabilized at 3.2 MPa over the 720 day period. These findings underscore the growing importance of AAC within the construction sector, particularly due to its reproducible and reliable experimental results, as the industry increasingly shifts toward more sustainable alternatives to traditional cement-based materials.

- **Comparison of dielectric properties, radiation shielding, and electrical resistivity of alkali-activated blast furnace slag and Portland cement binders/ Mehedi Rabbil, Mikko Kokkonen, Elijah Adesanya, Otto Mankinen, Mohammad Bhuyan, Sherif Hegazy, Sami Myllymaki, Juho Yliniemi, Tero Luukkonen. (2025) Materials and Design**

  DOI: 10.1016/j.matdes.2025.114763

  Alkali-activated materials (AAMs) are increasingly explored for sustainable construction, yet their electromagnetic and radiation-related properties remain largely unknown. This study explored the radio wave propagation, gamma-ray shielding efficiency, and electrical resistivity of alkali-activated blast furnace slag (BFS-AAM) compared to hydrated Portland cement (PC). BFS-AAM demonstrated superior relative permittivity (εr ≈ 7.6 at 2.4 GHz) and loss tangent (~0.33) at lower radio frequencies (0.02–10 GHz), leading to enhanced signal attenuation compared to PC (εr ≈ 5.6, loss tangent ≈ 0.07). BFS-AAM showed similar performance to PC at frequencies between 10–20 GHz, while its characteristics below 10 GHz make it suitable for secure signal environments. In terahertz spectrum (0.2–2 THz), relevant for 6G wireless communication, both materials displayed comparable permittivity (~5.3 and ~4.2) and loss tangent (~0.09 and ~0.04), indicating compatibility with residential and commercial applications. Simulations at 0.7, 2.4, and 6.0 GHz confirmed higher signal attenuation by BFS-AAM. Additionally, BFS-AAM exhibited

higher resistivity (26–110 Ω·m), greater compressive strength (60 MPa), and lower porosity (~11 %), contributing to its favorable dielectric properties. Although BFS-AAM demonstrated slightly lower gamma-ray shielding efficiency (at 0.661 MeV) than PC, its multifunctional properties position it as promising material for advanced electromagnetic and radiation shielding technologies.

- **Exploring the potential of lithium tailings in construction materials/ Anshumali Mishra, Parinus Vedadi, Nusrat Binte Kabir, Allen Yushark Fosu, Quentin Dehaine, Pasi Heikkilä, Ndue Kanari, Hilde Chambart, Mikko Räisänen, Priyadharshini Perumal. (2025) Minerals Engineering**

  DOI: 10.1016/j.mineng.2025.109678

  Lithium mining generates substantial quantities of tailings, posing environmental and resource recovery challenges. This study evaluates the potential reuse of lithium tailings from three prospective lithium mine projects as alternative construction materials, including alkali-activated materials (AAMs), supplementary cementitious materials (SCMs), lightweight aggregates (LWAs), and ceramics (CMS) through characterization and categorization investigation. Mineralogical analysis indicates the presence of silicate minerals, hydroxide-bearing silicates, sulfates, and carbonates. Particle size analysis shows that slimes (M3S) have a finer distribution (D_{50} = 5 µm), favouring AAMs and SCMs use, while coarser M1S and M2S (D_{50} = 100 µm) are better suited for LWAs. Among the samples, M3M exhibits the highest BET surface area (1.74 m^2/g), enhancing its reactivity for SCMs and CMS applications. Leaching tests confirm that all samples comply with EU landfill directive limits, indicating environmental safety. Thermogravimetric analysis shows mass losses of 0.5 wt% and 1.1 wt% for M1S and M2S, respectively, suggesting insignificant differences in phase transformations. Isothermal calorimetry reveals that M3D has the highest heat release (57 J/g), indicating potential for early-age hydration; however, overall pozzolanic activity remains limited. A machine learning approach using XGBoost, Random Forest, Histogram-based Gradient Boosting, and AdaBoost was applied to predict promising applications based on characterization data. While most models agreed on classification, AdaBoost frequently identified CMS as a promising use. Overall, the findings indicate that lithium tailings are environmentally benign and technically promising for proposed construction applications, contributing to a circular, resource-efficient, and zero-waste approach to lithium mining.

- **Sustainable valorization of MSWI residues: Mechanochemical immobilization of heavy metals and use as supplementary cementitious materials/ Tuan Van Truong, Gunvor M Kirkelund, Priyadharshini Perumal. (2025) Journal of Environmental Management**

  DOI: 10.1016/j.jenvman.2025.127600

Potentially toxic elements (heavy metals and chlorinated organic compounds) and metallic aluminum (Al^0) in municipal solid waste incineration (MSWI) residues pose a critical barrier to their utilization as cementitious materials. In this study, the mechanochemical treatment of all types of MSWI residues - individually, together, or with CaO was carried out to immobilize heavy metals, mitigate highly toxic organic compounds, and enhance cementitious properties. The leaching rate of Sb from the original bottom ash (BA), as well as Cr, and Pb from the air pollution control (APC) residues, was reduced by 99.9 %, 57.4 % and 54.4 %, respectively, to a non-hazardous limit after treatment. The highly toxic chlorinated organic compounds in the APC residues were converted to less toxic forms following treatment. Changes in bonds and chemical states can help elucidate the mechanisms of mechanochemical treatment. However, increased metallic Al in the fly ash (FA) after milling deteriorated the mechanical properties of the cement mortar. Contrarily, the treatment of FA with CaO addressed the metallic Al issue and enhanced the strength of the cement mortar up to 47.4 MPa at 28 days that equalled the CEM I reference. The mechanochemical treatment of MSWI residues with CaO enhanced remarkably the compressive strengths of their cement mortars. The mechanochemical treatment of a mixture of BA, FA, and APC in suitable fractions transformed MSWI residues into non-hazardous substances with demonstrated potential as supplementary cementitious materials (SCMs), offering a comprehensive pathway for utilization.

- **Carbonated recycled concrete aggregates in construction: potential and bottlenecks identified by RILEM TC 309-MCP/ Yury A Villagran-Zaccardi, Lucy Ellwood, Priyadharshini Perumal, Jean Michel Torrenti, Zengfeng Zhao, Ellina Bernard, Theodore Hanein, Tung Chai Ling, Wei Wang, Zhidong Zhang, Ruben Snellings. (2025) Materials and Structures/Materiaux et Constructions**

  DOI: 10.1617/s11527-024-02489-6

  This review by Working Group 1 of the RILEM TC 309-MCP discusses recent advances in the beneficial carbonation treatment of recycled concrete aggregates (RCA). The impact of carbonation on RCA properties as well as the microstructure and performance of concrete and other construction materials made thereof is critically reviewed. The increasing focus on environmentally friendly building practices has led to a greater interest in the CO2 uptake associated with carbonation processing. Furthermore, emphasis is placed on the importance of adopting tailored strategies to optimise the carbonation process based on the quality and type of RCA. Evidence in the literature highlights the beneficiation potential of carbonation processing in improving RCA properties and performance, which translates in variable degrees of enhancement of the performance of concrete or other applications made thereof. The review concludes that, to date, significant techno-

economic challenges remain to be addressed to improve the competitiveness of the technology, notably in terms of upscaling and refining life cycle assessment data.

- **Dissolution–precipitation reactions of blast furnace slag and sodium carbonate with 2,3-dihydroxynaphthalene/ Rajeswari Ramaswamy, Juho Yliniemi. (2025) Nanoscale**

  DOI: 10.1039/d4nr04251d

  Chemical admixtures are needed to enhance the reactivity of the industrial waste by-products to expand their utilization in the cement and concrete industry to create low CO_2 sustainable binders. One such chemical admixture which is a complexing ligand (2,3-dihydroxynaphthalene) has been shown to accelerate the hydration kinetics and enhance the mechanical strength (from 2 MPa to 40 MPa) of sodium carbonate-activated blast furnace slag binder. This study aims to understand the working mechanism of 2,3-dihydroxy naphthalene as an accelerator and the formation of the micro- and nano-surface precipitates for sodium carbonate-activated slag through batch dissolution experiments. Both solution (pH evolution, element concentration, organic and inorganic carbon content) and solid (identification and chemical composition of the phases) chemistry were investigated using various analytic and microscopic techniques. The results showed that the ligand significantly increased the extent of the slag dissolution, which affected the solution chemistry, consequently accelerating the precipitation kinetics. Further, the ligand affected the amount of precipitation (calcite and gaylussite) and the modification of Mg–Al–Si–Na–Ti-rich nano- and micro-sized precipitate morphology in the ligand system compared to the reference system. This work provides important information on ligand–carbonate–slag reactions, which pave the way for developing new chemical admixtures for a sustainable future.

- **Influence of additives on the hydration, pore chemistry and phase assemblage of ferrite-rich steel slag-based cement clinker/ Elijah Adesanya, Visa Isteri, Marco Cantaluppi, Juho Yliniemi. (2025) Case Studies in Construction Materials**

  DOI: 10.1016/j.cscm.2025.e05595

  Electric arc furnace slag (EAFs) was used as an alternative material for alite-ferrite (C_3S-C_4AF) clinker synthesis. Successful synthesis achieved 26 wt% and 70 wt% of C_4AF and C_3S, that was used for hydration investigation. The combined effect of triisopropanolamine (TIPA) and gypsum on the hydration kinetics, pore solution, and phase assemblage on the synthesized cement was investigated by using advanced characterization methods. The results showed the addition of gypsum delayed the hydration of C_4AF, reduced the Fe concentration in the pore solution and altered the

formation of hydrogarnet in the presence of TIPA. Whereas, in absence of gypsum and presence of 250 ppm of TIPA, Fe content in the pore solution increased, the hydration of C_4AF was enhanced, leading to formation of hydrogarnet and improving strength of the mortar. Lastly, the results show the effect of TIPA on ferrite hydration is dependent on the proportions of C_3S, C_4AF, and gypsum in cement.

- **Novel non-conventional raw materials as supplementary cementitious materials for low-carbon composite cement: Chemical reactivity, fresh and hardened state characterization/ Adeolu Adediran, Tuan Van Truong, Priyadharshini Perumal. (2025) Environmental Research**

  DOI: 10.1016/j.envres.2025.121146

  The incorporation of supplementary cementitious materials (SCMs) in cement-based construction is fast becoming an environmentally friendly option to reduce CO_2 emissions associated with cement production. Fifteen raw materials i.e. two conventional (blast furnace slag and fly ash) and thirteen non-conventional (fayalite slag, glass wool, stone wool, ladle slag, municipal solid waste incineration bottom ash, waste glass, high silicate mine tailings, high magnesium mine tailings, high alumina mine tailings, volcanic pozzolan Iceland, calcined Finnish clay, stainless steel slags, and precast concrete sludge) available in the Nordics were investigated as SCMs. The reactivity of the materials was compared using R^3 test while the fresh and hardened properties of cementitious pastes with a 30% SCM replacement level were investigated via isothermal calorimetry, setting time, rheology, electrical resistivity, compressive strength, thermogravimetry and differential thermogravimetry (TG-DTG), x-ray diffraction (XRD), and scanning electron microscope coupled with energy-dispersive x-ray spectroscopy (SEM-EDS). The results showed that there exists a difference in the reactivities, and properties among the samples, attributed to the differences in the chemical and mineralogical composition of the SCM. Based on R^3 test, blast furnace slag, fly ash, ladle slag, glass wool, stone wool, volcanic pozzolan Iceland, and calcined Finnish clay are classified as reactive materials (higher heat release and bound water) while the remaining SCMs are classified as inert or slow reacting materials. Strong correlations were found between chemical reactivity and paste properties as paste samples containing reactive materials as SCM performed better, exhibiting a reduction in setting time while having higher reactivity, compressive strength, electrical resistivity, and denser microstructure than those containing inert or slow reacting materials. Moreover, sustainable performance index based on the relationship between the availability and reactivity criteria of SCMs was developed.

- **Recycling analcime residues of lithium production from spodumene ore in eco-friendly cementitious binders/ Patrick N. Lemougna, Srujana Gouda, Adeolu Adediran, Visa Isteri, Pekka Tanskanen, Katja Kilpimaa. (2025) Case Studies in Construction Materials**

  DOI: 10.1016/j.cscm.2025.e04556

  There is an increasing need for supplementary cementitious materials (SCMs) to ensure the sustainability of concrete production. This study investigates the potential of using analcime-rich material, a byproduct of lithium refining from spodumene, as a means of reducing clinker content in concrete while also finding a suitable application for this type of industrial residue. The production of analcime residue is expected to rise in the future due to the green transition and the increasing demand for batteries. Cement was substituted with analcime residue at 10, 15, 20, and 30 wt.% in the preparation of pastes and mortars. These mixtures were characterized for their fresh and hardened state properties using isothermal calorimetry, rheology, setting time analysis, compressive strength testing, X-ray diffraction (XRD), thermogravimetric analysis (TG/DTG), and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS). The Rapid, Reliable, Relevant (R^3) test revealed that analcime residue exhibited a cumulative heat release of 278 J/g and bound water content of 5.4 g per 100 g of residue, indicating moderate reactivity. SEM-EDS analysis further confirmed the reactivity of the analcime residue. The substitution of cement with 10 wt.% analcime residue resulted in mortars with comparable rheological and mechanical properties to the reference sample, achieving compressive strengths of 45 MPa at 28 days and 57 MPa at 90 days. Although strength decreased with increasing analcime residue content, samples prepared with 30 wt.% substitution still exhibited a strength activity index exceeding 75% at 28 days, demonstrating its potential as a partial clinker replacement in sustainable concrete production.

- **Improving thermal insulation and thermal resistance properties of laterite-based geopolymer foams by direct foaming/ Julson Aymard Tchio, Joelle Nadia Nouping Fekoua, Cyriaque Rodrigue Kaze, Juvenal Giogetti Deuton Nemaleu, Juho Yliniemi, Elie Kamseu, Florence Uphie Chinje, Cristina Leonelli. (2025) International Journal of Applied Ceramic Technology**

  DOI: 10.1111/ijac.14959

  This work aims to synthesize new foaming laterite geopolymer foam using laterite, sodium silicate solution, sand, and aluminium powder. The porosity rapidly increased with the addition of the foaming agent. The foam matrix had thermal conductivity values of 0.10 W/m K with 0.7% of Al powder and 0.64 W/m K with 0% of Al powder. For fire resistance, samples exposed to high temperatures (200°C and 500°C)

showed increased flexural strength, linear shrinkage at 500°C, and a decrease at 900°C due to structural weakening under high thermal pressure and the appearance of new phases such as nepheline and akermanite in X-ray diffraction analysis. The results also showed that a 30% increase in fine aggregate content increased the strength of the foam matrix, with flexural strength ranging from 5 to 9.1 MPa after 28 days of ambient curing. These laterite geopolymer foams have shown promising thermal insulation and mechanical qualities that are appropriate for building applications.

- **Opening Letter of RILEM TC UMW: Upcycling Powder Mineral Wastes into Cement Matrices — Challenges and Opportunities/ Arne Peys, Luca Valentini, Aniruddha Baral, Arezou Babaahmadi, Priyadharshini Perumal, Marco Davolio, Liberato Ferrara, Antonios Kanellopoulos, Theodore Hanein. (2025) RILEM Technical Letters**

  DOI: 10.21809/rilemtechlett.2025.210

  The cement and concrete industries are currently facing the urgent and arduous challenge of decarbonisation and material circularisation for improved resource efficiency. The pursuit of new raw materials and binders that will improve sustainability is urgent, especially as end-of-pipe carbon capture and storage (CCS) technologies have not yet been scaled up economically even after five decades of research and large investments. On the other hand, society is facing the colossal issue of managing mineral wastes which are produced in several Gts per year globally, posing a massive environmental and societal liability. Many of these mineral wastes have elemental and mineralogical profiles that make them good candidates for use as clinker raw feed or supplementary cementitious materials. Although the published research on the topic is extensive, it is not organised, lacking a systematic comprehensive approach, making valorisation challenging. RILEM TC UMW was developed to address this gap and create a framework for realising the potential of upcycling mineral wastes focusing on using powders as either clinker raw feed or other binder applications while excluding discussion on calcined clays and mineral carbonation.

- **Co-calcination of kaolinitic clay and green liquor dregs to produce supplementary cementitious materials/ Elijah D. Adesanya, Alastair T.M. Marsh, Sreejith Krishnan, Juho Yliniemi, Susan A. Bernal. (2025) Case Studies in Construction Materials**

  DOI: 10.1016/j.cscm.2025.e04520

  This study investigated the effect of the co-calcination temperature (600, 700, and 800 °C) and the blending ratio of green liquor dreg (GLD) and kaolinitic clay (2:1, 1:1,

1:2) to produce a limestone calcined clay (LC2)-type supplementary cementitious material (SCM). The phase assemblage and hydration process of composite cements comprising CEM I and varying replacement ratios (15 and 30 wt%) of the produced SCM were evaluated. An effective co-calcination temperature of 700 °C was identified considering the chemical reactivity of the LC2-type SCM determined by the rapid, relevant, and reliable (R^3) testing. X-ray diffraction and scanning electron microscopy showed variations in the phase assemblage of the composite cements and the reference CEM I. Calcium carbonate from GLD and metakaolinite from the calcined clay contributed to the formation of carboaluminate in the composite cements, lowering its porosity. The 7- and 28-day compressive strengths of the mortars produced by replacing 15–30 wt% of the cement with this SCM, were comparable to those of the CEM I reference mortar. These findings demonstrate the industrial symbiosis potential between the paper and cement industries via applying co-calcination for resolving challenges for utilization of GLD, while producing a suitable kaolinitic clay based SCM.

- **Alkali Activation of Metakaolin and Wollastonite: Reducing Sodium Hydroxide Use and Enhancing Gel Formation through Carbonation/ Veronica Viola, Prince Allah, Priyadharshini Perumal Michelina Catauro. (2024) Materials**

  DOI: 10.3390/ma17194910

  Alkali activated materials (AAMs) offer significant advantages over traditional materials like Portland cement, but require the use of strong alkaline solutions, which can have negative environmental impacts. This study investigates the synthesis of AAMs using metakaolin and wollastonite, aiming to reduce environmental impact by eliminating sodium silicate and using only sodium hydroxide as an activator. The hypothesis is that wollastonite can provide the necessary silicon for the reaction, with calcium from wollastonite potentially balancing the negative charges usually countered by sodium in the alkaline solution. This study compares raw and carbonated wollastonite (AAM-W and AAM-CW) systems, with raw materials carefully characterized and binding networks analyzed using TGA, FT-IR, and XRD. The results show that while wollastonite can reduce the amount of sodium hydroxide needed, this reduction cannot exceed 50%, as higher substitution levels lead to an insufficiently alkaline environment for the reactions. The carbonation of wollastonite enhances the availability of silicon and calcium, promoting the formation of both N-A-S-H and C-A-S-H gels.

- **A method of pretreating incineration ashes containing metallic aluminium using NaOH to mitigate volume expansion under highly alkaline conditions/ Suman Kumar Adhikary, Tero Luukkonen, Mohammad Amzad Hossain Bhuyan, Yangmei Yu, Priyadharshini Perumal. (2024) Construction and Building Materials**

DOI: 10.1016/j.conbuildmat.2024.138639

Globally, millions of tonnes of incineration ashes are produced with a substantial portion remaining underutilized in low-value applications or disposed in landfills. Many types of fly ashes and bottom ashes contain metallic aluminium (Al0), which causes volume expansion when the ashes are used in alkali-activated materials and as a supplementary cementitious material due to the generation of hydrogen gas at high-pH conditions. This phenomenon significantly restricts the potential applications of these ashes. To address this issue, ashes can be pretreated with NaOH to oxidize the metallic aluminium (Al0) before their utilization. This study focuses on investigating the effect of the NaOH pre-treatment duration on fly ashes from the co-combustion of recovered solid fuel, peat, and wood. A pre-treatment process was conducted using 8 mol/L aqueous NaOH solution to treat the fly ash for up to 60 minutes. The formed slurry was subsequently used to prepare alkali-activated material by mixing it with bottom ash and employing either sodium silicate or sodium carbonate as an alkali activator. The NaOH pre-treatment demonstrated a 100 % metallic aluminium conversion into oxidized form resulting enhancement in mechanical performance, microstructure, and water absorption properties. The proposed method offers a highly efficient and rapid solution for eliminating the drawbacks caused by the presence of metallic aluminium and it can be conveniently implemented on construction sites. Concurrently, this study also explores the leaching behaviour of heavy metals during alkali-activation. Significant reductions in the leaching of Ba, Cr, Cu, Mo, and Pb were observed, highlighting the environmental remediation potential of alkali-activation methods.

- **Separation of microplastics from water using superhydrophobic silane-coupling-agent-modified geopolymer foam/ M.A.H. Bhuyan, R. Busquets, L.C. Campos, T. Luukkonen. (2024) Separation and Purification Technology**

DOI: 10.1016/j.seppur.2024.126709

Microplastics are a topical environmental problem that requires urgent solutions. They are ubiquitously present in various wastewaters and are discharged into aquatic environments because of difficulties in their removal. In this study, a novel filtration medium, superhydrophobic geopolymer foam, was prepared and investigated for the separation of microplastics from water. The foam was prepared using metakaolin, sodium silicate, sodium hydroxide, hydrogen peroxide, and Triton X-100 surfactant as raw materials and superhydrophobized with a silane coupling agent, triethoxy(octyl)silane. The purpose of the superhydrophobization was to improve the attachment of hydrophobic microplastic particles to the foam surface via chemical interactions. The modified geopolymer foam exhibited a water contact angle of 152°, and the presence of octyl chains on its surface was confirmed using Fourier transform

infrared and X-ray photoelectron spectroscopies. When applied as a filter, the modified foam separated 53-63-µm sized polyethylene microspheres with ~99 % removal efficiency, and no change in its separation efficiency was observed for ~200 bed volumes of treated water. A comparison with an unmodified foam filter confirmed that the removal mechanism was not based on physical separation at higher flow rates, because the performance of the unmodified foam began to degrade after treating ~5 bed volumes of wastewater. The performance of the modified foam was also validated with laundry washing effluents (particle size of microplastics varied roughly within 2–2000 µm), achieving ~84 % separation efficiency for ~50 bed volumes of wastewater. This study provides proof of concept of using superhydrophobic geopolymers as efficient, easy-to-prepare, and potentially low-cost separation media for microplastics from water effluents.

- **Fe-bearing magnesium silicate glasses for potential supplementary cementitious applications/ Chuqing Jiang, Hellen Silva Santos, Juho Yliniemi, Johan Lindén, D. D. Ramteke, Mirja Illikainen, Christopher Cheeseman, Päivö Kinnunen. (2024) Frontiers in Materials**

  DOI: 10.3389/fmats.2024.1509403

  Supplementary cementitious materials (SCMs) are used to minimize CO_2 emissions associated with cement production. However, their global supply is insufficient to meet the growing market demand for cement and concrete, being essential to develop alternative SCMs based on abundant waste streams and low-cost resources. Fe-bearing Mg-based glasses are promising candidates with the potential to utilize high-volume feedstocks rich in Fe and Mg, but their effectiveness relies on deep understanding of the relationship between glass composition, reactivity, and pozzolanic properties. In this study, Fe-Mg silicate glasses with varying Fe concentrations were precisely engineered through a sol-gel route to better understand the impact of Fe on the glass structure and reactivity. While Fe^{3+} typically acts as a glass network former, it was observed to also function as an intermediate cation, behaving either as a network former or modifier. Glass reactivity was assessed through aqueous dissolution tests, revealing that the composition and chemical environment of Fe^{3+} within the glass network significantly influence the dissolution behavior. The introduction of Fe into Mg-Si glasses increased overall reactivity, potentially due to Fe-induced phase separation and the increasing of $[FeO_6]$ octahedra sites at higher Fe concentrations, which was also associated to network depolymerization. These findings deepen the understanding of the role of Fe^{3+} in magnesium silicate glasses, provide key insights into optimizing glass reactivity by fine-tuning the composition, and indicate the potential of these glasses as promising SCMs.

- **Sustainable reuse of magnesite mine tailings in cement-treated expansive soil for enhanced subgrade performance: geotechnical and environmental analysis/ Vinodhkumar Shanmugasundaram, Balaji Shanmugam, Ponnusamy Kulanthaivel, Priyadharshini Perumal. (2024) Journal of Taibah University for Science**

  DOI: 10.1080/16583655.2024.2397861

  This study explores the use of Magnesite Mine Tailings (MMT) as an admixture in cement stabilization of Expansive Soil (ES) to improve subgrade performance and reduce environmental impact. Various combinations of Ordinary Portland Cement (OPC) and MMT were investigated using standard proctor compaction, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), durability and Toxicity Characteristic Leaching Procedure (TCLP) tests. Results showed enhanced ES strength with MMT and OPC, with a maximum UCS of 1179 kPa and a soaked CBR of 25.1% after 28 days. However, higher cement content (>12%) is necessary for durability and meeting environmental regulations. X-Ray Diffraction and Field Emission Scanning Electron Microscopy confirmed hydration products, supporting MMT as a sustainable solution for stabilization and tailings disposal.

- **Upcycling spodumene tailings in the preparation of high alumina porcelain composition sintered at 1200–1400 ˚C/ Patrick N. Lemougna, Nahal Abie, Arnold Ismailov, Erkki Levanen, Pekka Tanskanen, Katja Kilpimaa, Mirja Illikainen, Priyadharshini Perumal. (2024) Minerals Engineering**

  DOI: 10.1016/j.mineng.2024.108937

  Concentration of spodumene from lithium pegmatite ore generates large amounts of tailings that need to be recycled for sustainability and circular economy concerns. This study investigated the preparation of high-alumina porcelain compositions incorporating spodumene tailings, i.e., quartz feldspar silt (QFS). The mix design closely matched the theoretical composition of 60.51-wt.% Al2O3, 34.34-wt.% SiO2, 2.98-wt.% K2O, 0.66-wt.% Na2O, and 0.33-wt.% CaO. For comparison, a reference composition free of QFS, composed of commercial materials, was also prepared. Both compositions were thermally treated at 1200℃, 1300℃, and 1400℃. The prepared samples were characterised using several techniques, including X-ray diffraction, scanning electron microscopy–energy-dispersive X-ray spectroscopy, thermogravimetry/differential scanning calorimetry, compressive and flexural strength tests, water absorption, apparent density, and dilatometry at high temperatures up to 1400℃. The results show that corundum and mullite are the primary crystalline phases formed at high temperatures in addition to an amorphous glassy phase. The compressive and flexural strengths were 25–60 and 6–10 MPa, respectively. QFS milling favoured phase densification, resulting in greater sintering

shrinkage. However, all samples were relatively stabilised after the first heating cycle and exhibited less than 1% dimensional changes during the second heating cycle at 1400℃. The reference and 26.4-wt.% QFS samples exhibited comparable results, indicating the potential for upcycling spodumene tailings as feldspar substitutes in the development of corundum-mullite based-ceramics for possible high temperature applications.

- **Regeneration of metal-containing alkali-activated adsorbent granules from a field experiment/ Nusrat Kabir, Jenna Finnilä, Johanna Laukkanen, Tero Luukkonen. (2024) Chemical Engineering Research and Design**

  DOI: 10.1016/j.cherd.2024.11.017

  Alkali-activated materials have become an active research topic as adsorbents for wastewater treatment. However, their regeneration is studied less frequently. In the present study, granular alkali-activated adsorbents were prepared from metakaolin or blast furnace slag with an inclusion of commercial $MgCO_3$/MgO/Mg silicate-rich mineral adsorbent. The granules were used in a field experiment to treat effluent from a closed mine site containing 4.3 mg/L Ni, 1.3 mg/L Mn, 0.5 mg/L Fe, and 0.6 mg/L Zn. The granule regeneration was compared with 0.3 M NaOH, 0.3 M NaCl, 0.03–1.5 M HNO_3, 0.3 M CH_3COOH, and 0.05 M EDTA-2Na solutions. The best-performing granule type was based on blast furnace slag with the commercial Mg-rich adsorbent and it could be regenerated effectively with 0.3 M HNO_3. The adsorption performance of the granules improved upon repeated regeneration (cumulative adsorption amounts in the field experiment reaching up to 1.0 mg/g Ni, 0.3 mg/g Mn, 0.1 mg/g Fe, and 0.2 mg/g Zn per cycle) which was likely due to enhanced specific surface area (reaching up 160–190 m^2/g while the initial values were 0.5–20 m^2/g). The granules had a mass loss of 27 % and 9.5 % during the first and second regeneration cycle, respectively, which is likely the limiting factor in their continued reuse.

- **Frost durability of cementitious materials: What's next?/ Magdalena Rajczakowska, Iveta Novakova, Adeolu Adediran, Priyadharshini Perumal, Olafur ´ Haralds Wallevik, Andrzej Cwirzen. (2024) Case Studies in Construction Materials**

  DOI: 10.1016/j.cscm.2024.e04014

  Frost durability, a critical parameter for concrete, especially in harsh exposure regions, has been extensively researched, with almost four thousand papers published since the 1970s. However, a systematic mapping of this research is yet to be explored. This paper presents a novel approach based on Natural Language

Processing (NLP) and machine learning to semi-automatically analyze the existing literature on frost durability of cementitious materials. The aim is to identify research gaps and provide insights for future work, offering a comprehensive understanding of the freeze and thaw (FT) research area. Data sets containing academic abstracts on FT tests have been created, and the identified articles are topically structured using a latent Dirichlet allocation (LDA) topic modeling approach. The publication volume associated with each topic over time has been quantified, providing an overview of the research landscape. The results show that NLP and t-SNE effectively review large volumes of technical text data, identifying 12 dominant themes in FT research, such as mechanical properties and material composition. Over recent decades, there has been a shift from focusing on structural performance to emerging topics like cracking and Supplementary Cementitious Materials (SCMs). Additionally, t-SNE and K-means clustering revealed four main clusters, suggesting future research should focus on the FT durability of eco-friendly materials, accelerated testing, and enhanced FT durability materials. These findings not only facilitate the identification of gaps and opportunities for future work but also have practical implications for developing more durable and sustainable concrete.

- **Analysis of alkali-activated mineral wool-slag binders: evaluating the differences between one-part and two-part variations/ Elijah Adesanya, Rawia Dabbebi, Christine Rößler, Majda Pavlin, Zhenming Li, Tero Luukkonen, Juho Yliniemi, Mirja Illikainen. (2024) Journal of Material Cycles and Waste Management**

  DOI: 10.1007/s10163-023-01878-3

  Two synthesis pathways (one- and two-part) in alkali-activated binders were compared using ground granulated blast furnace slag (GGBFS), mineral wool (MW) activated using dry and liquid alkali activators with similar Na_2O/SiO_2 modulus. The effect of activator type on reaction kinetics, strength development, setting times, and durability shows that one-part synthesis does not only improve early strength, but also provide better durability properties. While the highest compressive strength (56 MPa, 90 days) was achieved for the one-part mix (DM), the reaction products (presence of Mg–Al layered double hydroxide and C–S–H-like phases) observed for both mortar mixes were similar. The DM mortars showed better resistance to sulfate attack than two-part mix (WM) mortars and sets faster. The results highlight the significance of the one-part pathways in the synthesis of alkali-activated materials.

- **Alkali-Activated Foams Coated with Colloidal Ag for Point-of-Use Water Disinfection/ Mohammad Amzad Hossain Bhuyan, Antti Karkman, Hanna Prokkola, Boyu Chen, Priyadharshini Perumal, Tero Luukkonen. (2024) ACS ES and T Water**

DOI: 10.1021/acsestwater.3c00711

Alkali-activated foams are ceramic-like materials prepared at near-ambient temperature. This study investigates them for point-of-use water disinfection, thus providing an alternative to ceramic filters fired at a high temperature. Alkali-activated foams with different compositions were characterized for the porosity, mechanical strength, shrinkage, and microstructure. The optimized foam, employing metakaolin as the raw material, was coated with a colloidal Ag solution. The disinfection performance and leaching behavior of the foams was followed in a continuous 10 week experiment, where clean water with a weekly pulse of contaminated water was distributed through the foam. The average inactivation of *Escherichia coli* with the Ag-coated foam was 2.84 $\log_{10}$, which was 1.27 units higher compared to foam without Ag. A quantitative polymerase chain reaction analysis and metagenomic sequencing verified that foams with and without Ag were both capable of reducing the microbial load. Furthermore, the changes induced by the foam with Ag on the microbial community composition, antibiotic resistome, and metal and biocide resistomes were significant. The leached concentrations of Ag, Na, Si, and Al were in accordance with the drinking water guidelines. Finally, a life cycle assessment indicated the possibility of reducing the global warming potential and the total embodied energy in comparison with a conventional ceramic filter.

- **Adsorption of methylene blue by composite foams containing alkali-activated blast furnace slag and lignin/ M. A. H. Bhuyan, T. Luukkonen. (2024) International Journal of Environmental Science and Technology**

DOI: 10.1007/s13762-023-05245-5

Adsorption is a promising method to remove dyes, such as methylene blue, from wastewater. In this study, a dynamic adsorption set-up was used to treat synthetic wastewater containing methylene blue by using alkali-activated blast furnace slag and lignin composite foam. The structure of the foam without lignin was first optimized by comparing cationic and non-ionic surfactants in the preparation of the foam via the direct foaming method. The selection of the surfactant affects the porosity and pore structure of the foam through different abilities to stabilize the gas–liquid interface and changes in the viscosity of the fresh-state paste. The foam prepared with non-ionic Triton X-114 surfactant had the highest adsorption performance and was selected for the optimization of adsorption conditions. The optimized conditions were 5 mg/L influent concentration of methylene blue, pH of 7, and flow rate of 1.0 L/h (corresponding to ~ 9 min empty bed contact time). To further enhance the methylene blue adsorption performance, a composite containing lignin was prepared. The optimum lignin amount in the foam was 0.8 wt% and it resulted a ~ 93% higher adsorption amount compared to the foam without lignin. The highest cumulative adsorption capacity in this dynamic adsorption setup was 39.5 mg/g, which is among

the highest reported values for methylene blue removal by monolithic adsorbents. The present study provides a proof of concept for the enhancement of adsorption performance of alkali-activated materials by introduction of lignin into the structure.

- **Utilization of pretreated green liquor dregs as an activator for blast furnace slag: Effect on hydration, phase assemblage, and rheology/ Juho Rasmus, Elijah Adesanya, Katja Kilpimaa. (2024) Journal of Environmental Management**

  DOI: 10.1016/j.jenvman.2024.123021

  This study explores the utilization of calcium- and magnesium-rich pulp mill residues, i.e., green liquor dregs (GLDs), as an activator for ground granulated blast furnace slag (BFS). The aim of this study is to examine the potential of this unutilized residue when used as a part of alkali-activated materials (AAMs) and in this way enhance the exploitation of GLD. This study focuses on the fresh- and hardened-state properties of the produced paste and mortar samples, where 70% of BFS and 30% of GLD have been incorporated. Two different-sourced and thermally pretreated (105 °C, 300 °C, and 525 °C) GLDs have been used. The effect of thermal treatment on the utilization possibility of GLDs with respect to viscosity, setting times, reactivity, mineralogy, and microstructure is analyzed using the paste samples, while its effect on workability, and strength gain is measured using the mortar samples. Results show that both GLDs enhance the hydration of BFS and that the early-age hydration and strength increase when the GLDs have undergone pretreatment at the highest temperature (525 °C). However, at the later age (28 days), the samples activated with the GLDs treated at 300 °C achieve the highest strength. The addition of both GLDs treated at any temperature increases the viscosity of the composite samples and reduces their workability; however, it should be noted that optimization of water to binder ratio was not the objective of this study. The results of this study show that GLD, previously considered unreactive, can potentially become a reactive component of AAMs.

- **Reverse osmosis reject water management by immobilization into alkali-activated materials/ Sima Kamali, Vitalii Ponomar, Giovanni Dal Poggetto, Cristina Leonelli, Katja Kilpimaa, Tero Luukkonen. (2024) Desalination**

  DOI: 10.1016/j.desal.2024.117859

  Water-intensive industries face challenges due to water scarcity and pollution. In the management of these challenges, membrane processes play an important role. However, they produce significant amounts of reject waters, in which the separated salts and pollutants are concentrated. This study aims to develop a novel management concept for reject waters using alkali activation to immobilize salts in a solid phase using metakaolin, blast furnace slag (BFS), or their mixture as precursors

and to create alkali-activated materials with sufficient properties to be potentially used in construction applications. Seven different waters were used to prepare the NaOH-based alkali activator solution: deionized water, three simulated seawaters with increasing salinity, and three reverse osmosis (RO) reject waters from mining or pulp and paper industries. Overall, BFS-based samples had the highest immobilization efficiency, likely due to the formation of layered double hydroxide phases (hydrotalcite, with anion exchange capacity) and hydrocalumite (chloride-containing mineral). Moreover, high-salinity water enhanced the dissolution of precursors, prolonged the setting time, and increased the compressive strength compared with nonsaline water. Thus, the obtained materials could be used in construction applications, such as backfilling material at mines where RO concentrates are commonly produced.

- **Assessing the carbonation potential of wood ash for CO2 sequestration/ Veronica Viola, Michelina Catauro, Alberto D'Amore, Priyadharshini Perumal. (2024) Low-Carbon Materials and Green Construction**

  DOI: 10.1007/s44242-024-00043-9

  Wood ash, a byproduct of wood combustion, poses environmental challenges when disposed of in landfills. This study explores a sustainable alternative by investigating the carbonation of wood ash, a process converting CO_2 into stable carbonate minerals. With increasing concerns about waste management, this research aims to identify optimal carbonation conditions by varying relative humidity, liquid-to-solid ratio (*L/S*), and temperature. Results demonstrate that the ideal conditions for wood ash carbonation involve a moderate relative humidity of 55%, room temperature at 25 °C, and a lower *L/S* ratio. Thermogravimetric analysis (TGA) indicates that extended curing times increase $CaCO_3$ formation. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) confirm the presence of carbonate phases. Mechanical strength tests reveal that samples with lower porosity and higher carbonation products exhibit superior strength. This study contributes to the understanding of wood ash carbonation but also emphasizes its potential practical applications in construction materials as light aggregates in cement concrete. The research explores the implications for sustainable waste management, offering insights into environmentally and economically viable solutions for wood ash recycling.

- **Hydration and carbonation curing of high ferrite clinker (FePC) synthesized using EAF slag/ Elijah Adesanya, Visa Isteri, Aniruddha Baral, Christiane Rößler, Theodore Hanein, Juho Yliniemi. (2024) Low-Carbon Materials and Green Construction**

  DOI: 10.1007/s44242-024-00051-9

This study explores the use of Electric Arc Furnace (EAF) slag as a sustainable alternative raw material in cement clinker production. The research demonstrates the synthesis of ferrite-rich clinker using EAF slag, achieving a clinker composition of 47% alite, 32% ferrite, and 20% belite while replacing 20% of clinker raw materials i.e. limestone, iron and silica source. The hydration behavior and influence of carbonation curing on the reactivity of the ferrite phase were assessed. Results show that the addition of 5% gypsum to the clinker enhanced the hydration rate of alite and ferrite phases, promoting the formation of portlandite, C-S-H and ettringite as the major hydration phases. Typical of ferrite-rich cement, Fe/Al-rich siliceous hydrogarnet was also identified as secondary hydration products of the ferrite phase, formed as a result of the reaction of katoite (formed from ferrite dissolution) with dissolved silica. However, prolonged carbonation exposure led to a decrease in the formation of the hydrogarnet and the decomposition of ettringite, but the mortar's strength increased with increasing calcium carbonate formation.

- **Utilization of calcite-rich Green Liquor Dregs (GLD) by-products from pulp and paper industry: Cement clinker production and life cycle analysis/ Sumit Srivastava, Samira Moukannaa, Visa Isteri, D.D. Ramteke, Priyadharshini Perumal, Damilola Adesanya, Paivo Kinnunen, Katja Ohenoja, Mirja Illikainen. (2024) Case Studies in Construction Materials**

  DOI: 10.1016/j.cscm.2024.e02870

  The pulp and paper industry produces several calcite-rich by-products including Green Liquor Dregs (GLDs), lime mud, grits, sludges, etc. Presently, majority of these by-products are managed by landfilling. The GLD used in this study is mainly dominated by calcite (~80 %) and Hydrotalcite like compounds (HTlc, ~12 %). It is used to produced OPC clinkers by using them as 0 %, 5 %, 10 %, 15 %, and 20 % replacement of limestone used for clinker production. TGA-DSC analysis of the clinker raw meals up to 1350 ℃ indicates that increase in GLD leads to slight reduction in the decomposition temperature for the raw meals, and a slight change in the formation temperatures for C2S and C3S. The mineral phase compositions of all the clinkers are comparable with a slightly decreasing C3S and C2S with increasing GLD. Compared to the Bogue calculated compositions, C3S and C2S are slightly lower, while the C3A is significantly lower and C4AF is significantly higher. The environmental leaching of GLD and the clinkers are all within the limits set by EN-12457-2. The environmental impact of clinker production and effect of GLD is analyzed for cradle-to-gate scenario with system boundaries. This analysis shows that by using GLD as replacement for limestone can lower the impact on diversity as well as CO2 related to transportation can also be reduced.

- **Two-step process to recover metal and mineral residues from municipal solid waste incinerated (MSWI) ashes/ Tuan Van Truong, Priyadharshini Perumal, Maria Kokko, Janne Pesonen, Ulla Lassi, Mirja Illikainen. (2024) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2024.139341

  The utilization potential of mineral fractions after metal recovery from fly ash and air pollution control residues from a municipal solid waste incineration plant was studied. Chemical leaching using acidic (H2SO4), and alkaline (NaOH) solutions was applied for metal recovery from fly ash and air pollution control residues from a municipal solid waste incineration plant. Subsequently, the feasibility of recycling both untreated and treated samples in cementitious materials was evaluated. This study aims to investigate the influences of chemical leaching on the structures and properties of MSWI residues as well as examine the utilization potential in cementitious materials of mineral residues after leaching, and their environmental risk. The use of acidic and alkaline leachants had good efficiency in critical metal recovery and unvalued/hazardous metal removal: 99 % of As, 72–80 % of Cd, 47–60 % of Zn, Cu, Co or Mn. After leaching, the chemical composition, physical properties, and mineralogical phases of the incinerated residues were substantially modified. The postleaching mineral residues showed potential for use in supplementary cementitious materials with enhanced reactivity and control of hydration kinetics. The compressive strength of cement pastes using 20 % of MSWI residues can obtain 14 MPa after 7 days. Detrimental impacts from potential toxic elements in incinerated residues can be alleviated through chemical leaching.

- **Wood fly ash and blast furnace slag management by alkali-activation: Trace elements solidification and composite application/ Shayan S. Narani, Sumi Siddiqua, Priyadharshini Perumal. (2024) Journal of Environmental Management**

  DOI: 10.1016/j.jenvman.2024.120341

  Wood and biomass are burned in many industries as a sustainable energy source. The large quantities of fly ash produced must be landfilled, leading to environmental concerns. Precipitator wood fly ash (PFA) and ground granulated blast furnace slag (BFS) have been used in this study to prepare alkali-activated composites to manage and recycle the fly ash. After an essential characterization, the influence of parameters such as PFA and BFS content, alkaline activator content (silica moduli of 0, 0.82, 1.32), curing method, and curing duration on the mechanical, chemical, and microstructural properties of the samples have been studied through compressive strength, density, FTIR, and SEM-EDS investigations. The environmental safety and influence of polycondensation on heavy metal stabilization have been examined

through ICP-MS. The results prove that oven and hydrothermal curing obtain the early age strength. Despite the variations of strength with duration and type of curing, the compressive strength of samples after 28 days of curing tends to close values for a constant PFA/BFS ratio, due to which the need for energy-intensive curing methods is addressed. ICP-MS shows that the composites can suitably solidify As, Cd, Ba, Cr, Pb, Mo, Se, Hg, Sr, Cu, and Zn. On the other hand, the composites were almost incapable of stabilizing Co and V. Unlike the case for mechanical properties; higher PFA content favours hazardous metal stabilization through polycondensation.

- **Sustainable application of industrial side streams as alternative fine aggregates for cement mortar/ Priyadharshini Perumal, Corentin Gouriou, Elijah Adesanya, Abhijit Mistri, Mirja Illikainen. (2024) Innovative Infrastructure Solutions**

  DOI: 10.1007/s41062-023-01334-z

  Increase in industrialization has led to the production of huge volume of side-stream materials that need safe disposal solutions. The present study proposes the use of local industrial side streams such as ferrochrome slag, phyllite dust and mine tailings as secondary raw materials for construction, mainly as fine aggregates. Four different cement mortar mixtures, with a combination of selected side streams as a sole, binary, and ternary blends were investigated. Workability, strength, and durability properties of the derived mortar mixtures were compared with mortar produced using standard sand as reference. Mortar mixtures with a ternary blend of side-stream fine aggregates resulted in a compressive strength of 68–72 MPa at 28 days, which is 30–40% higher than that of control mix. The addition of industrial side streams resulted in a denser microstructure and enhanced the mechanical properties. The durability performance of the mortar with alternative fine aggregates is comparable with those of standard sand.

- **Metallic aluminium in municipal solid waste incineration fly ash as a blowing agent for porous alkali-activated granules/ Tero Luukkonen, Yangmei Yu, Suman Kumar Adhikary, Sami Kauppinen, Mikko Finnilä, Priyadharshini Perumal. (2024) Royal Society Open Science**

  DOI: 10.1098/rsos.240598

  Porous alkali-activated materials are synthetic aluminosilicates that should be often produced as granules for practical applications. In the present study, municipal solid waste incineration fly ash with ~1.2 wt% of metallic aluminium was used as a novel blowing agent for metakaolin (their ratio ranged from 0% to 100%) with an aqueous sodium silicate solution as the alkali-activator and granulation fluid in high-shear granulation. The compressive strength of all granules was sufficient (≥2 MPa). Water

absorption indicated an increase in porosity as the fly ash content increased. However, X-ray microtomography imaging showed no clear correlation between the fly ash content and porosity. The granules exceeded the leaching limits for earth construction materials for antimony, vanadium, chloride and sulphate. Of those, antimony, chloride and sulphate could be controlled by decreasing the ash content, but the source of vanadium was identified as metakaolin. The increase in the fly ash content decreased the cation exchange capacity of the granules. In conclusion, the recommended fly ash content is equivalent to 0.3 wt% of Al^0 and the developed granules could be best suited as light-weight artificial aggregates in concrete where the additional binder would provide stabilization to decrease the leaching.

- **3,4-dihydroxybenzoic acid forms soluble complexes in cementitious systems/ Sepideh Bagheri, Otto Mankinen, Satu Ojala, Ville-Veikko Telkki, Tero Luukkonen, Juho Yliniemi. (2024) Journal of Non-Crystalline Solids**

  DOI: 10.1016/j.jnoncrysol.2024.122962

  Various amorphous multi-oxide silicates can be used as a precursor for cementitious binders. However, their dissolution kinetics are often slow and further inhibited by ions adsorbed on their surfaces. Organic ligands as complexing agents could enhance their extent of dissolution. Here, the effect of 3,4-dihydroxybenzoic acid (DHBA) with 1 mM concentration on early-stage dissolution of blast furnace slag and basaltic glass was investigated at pH 12–14. DHBA impacted the dissolution depending on the pH and composition of the raw material. Liquid-state ^{13}C and ^{1}H NMR spectroscopy proved fast formation of two types of soluble complexes: 1) complexation between phenolic groups of DHBA and Al^{3+}, Mg^{2+}, Ca^{2+} and Fe^{3+}, and 2) complexation between carboxylic groups of DHBA and Fe^{3+}. Thermodynamic modelling of solution and precipitation chemistry showed that experimental results are in line with modelling. X-ray photoelectron spectroscopy indicated that DHBA prevents the accumulation of cations on the silicate surface.

- **Alternative construction materials from industrial side streams: Are they safe?/ Suman Kumar Adhikary, Antonio D'Angelo, Veronica Viola, Michelina Catauro, Priyadharshini Perumal. (2024) Energy, Ecology and Environment**

  DOI: 10.1007/s40974-023-00298-1

  The global population is continually generating vast amounts of waste materials across various sectors, leading to environmental challenges associated with landfill disposal. This study aims to examine the leachate and the antimicrobial properties of several waste materials to explore their potential applicability in the construction

industry. Here, ICP-OES analysis and Kirby Bauer test were conducted on ready-mix concrete plant (powder residues), precast industries, recycled alkali-activated materials, municipal solid waste incinerated (MSWI) bottom ash, MSWI fly ash, High alumina tailing, and High magnesia tailing, to explore their potential applicability in the construction industry. Aluminium, calcium, silicon, potassium, and magnesium were the major ions leached from the waste materials, with MSWI fly ash and bottom ash showing higher levels of heavy metal leaching. The levels of leached aluminium, barium, chromium, lead, and zinc from MSWI fly ash and bottom ash were quantified, with values reaching up to 28.7 ppm, 4 ppm, 3.9 ppm, 11 ppm, and 25 ppm, respectively. Additionally, all samples demonstrated some level of antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus,* which could be related to their alkaline pH and the release of certain ions. Improper disposal of waste materials in an open environment can potentially lead to contamination by heavy metals and harmful bacteria, which can pose a significant health risk during handling. This study results provided valuable information regarding the safety of using these wastes in the construction industry.

- **Influence of calcium oxide and hydroxide on non-ferrous metallurgical slag hydration in alkaline environments/ Vitalii Ponomar, Juho Yliniemi, Katja Kilpimaa. (2024) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2024.105673

  The search for new supplementary cementitious materials (SCMs) to reduce CO2 emissions has become increasingly vital in cement and concrete research. Non-ferrous metallurgical slag (NFMS), often overlooked due to their low pozzolanic and hydraulic reactivity, present a promising alternative, particularly given their enhanced reactivity in the presence of alkalis. This study explores the hydration behaviour of NFMS under varying concentrations of CaO, Ca(OH)2, and NaOH, with a focus on dissolution kinetics and phase evolution. 1 M and 6 M NaOH solutions were selected to examine the effect of calcium additives on NFMS hydration, representing scenarios without (1 M NaOH) and with (6 M NaOH) alkali activation reactions. In 6 M NaOH, the addition of CaO/Ca(OH)2 had a minimal impact on dissolution rates but significantly influenced phase assemblage, with CaO promoting strätlingite formation and 10 % Ca(OH)2/CaO leading to katoite. At higher replacement levels (20 % CaO/Ca(OH)2), phase formation was hindered, although microstructure densification persisted, accompanied by reduced strength. In 1 M NaOH, low concentrations of CaO/Ca(OH)2 enhanced Al and Si dissolution but had limited impact on phase assemblage. Higher CaO content favoured katoite formation, while Ca(OH)2 exhibited traces of hydrocalumite. Both additives improved microstructure, but CaO addition, associated with katoite formation, predominantly enhanced strength. The findings confirm that NFMS has significant potential as a cement replacement in hybrid systems utilizing high ratios of slag, Portland cement, and alkalis. By promoting

the formation of Ca-Al phases, NFMS improves microstructure and strength, making it a viable and environmentally friendly alternative in construction materials.

- **Why geopolymers and alkali-activated materials are key components of a sustainable world: A perspective contribution/ Waltraud M. Kriven, Cristina Leonelli, John L. Provis, Aldo R. Boccaccini, Cyril Attwell, Vilma S. Ducman, Claudio Ferone, Sylvie Rossignol, Tero Luukkonen, Jannie S. J. van Deventer, José V. Emiliano, Jérôme E. Lombardi. (2024) Journal of the American Ceramic Society**

  DOI: 10.1111/jace.19828

  This perspective article delves into the transformative potential of alkali-activated materials, acid-activated materials, and geopolymers in mitigating climate change and market challenges. To harness the benefits of these materials, a comprehensive strategy is proposed. This strategy aims to integrate these materials into existing construction regulations, facilitate certification, and promote market access. Emphasizing research and innovation, the article advocates for, increased funding to refine the chemistry and production of these materials, prioritizing low-cost alternatives and local waste materials. Collaboration between academia and industry is encouraged to expedite technological advances and broaden applications. This article also underscores the need to develop economic and business models emphasizing the long-term benefits of these materials, including lower life-cycle costs and reduced environmental impact. Incentivizing adoption through financial mechanisms like tax credits and subsidies is suggested. The strategy also includes scaling up production technology, fostering industrial collaboration for commercial viability, and developing global supply chains. Educational programs for professionals and regulators are recommended to enhance awareness and adoption. Additionally, comprehensive life-cycle assessments are proposed to demonstrate environmental benefits. The strategy culminates in expanding the applications of these materials beyond construction, fostering international collaboration for knowledge sharing, and thus positioning these materials as essential for sustainable construction and climate change mitigation.

- **Porous metakaolin geopolymer as a reactive binder for hydroxyapatite adsorbent granules in dye removal/ Aghilas Brahmi, Salima Ziani, Salima AitAli, Bachir Nadir Benkhaoula, Yangmei Yu, Hania Ahouari, Hafit Khireddine, Tero Luukkonen. (2024) Hybrid Advances**

  DOI: 10.1016/j.hybadv.2023.100134

In this study, porous hydroxyapatite-metakaolin geopolymer (HAP-MK-GP) granules were prepared with a novel method for adsorption of organic pollutants from aqueous solutions, using brilliant green dye as a model compound. The preparation involved combining finely powdered hydroxyapatite, metakaolin, and solid sodium metasilicate in a high-shear granulator. Then, hydrogen peroxide (H_2O_2) was added at different concentrations (0.0, 5.0, 7.5, or 10.0%) as a combined granulation fluid and blowing agent. In the resulting granules, metakaolin geopolymer bound the powdered hydroxyapatite as granules and contributed to the adsorption capacity. To determine their structural, morphological, and mechanical properties, the granules were characterized with infrared spectroscopy, X-ray fluorescence, scanning electron microscopy, specific surface area and porosity analysis, and compressive strength tests. The granules had a high porosity and promising compressive strength and Young's modulus of 0.8 and 10 MPa, respectively, potentially enabling their use in large-scale adsorption columns. The monolayer adsorption mechanism of brilliant green dye onto HAP-MK-GP granules was confirmed by fitting the obtained batch adsorption data to the Langmuir isotherm model which showed that the adsorption capacity was approximately 41 mg/g. The optimum conditions were: pH of 7, initial dye concentration of 100 mg/L, adsorbent dose of 3 g/L, agitation speed of 250 rpm, contact time of 30 min, and temperature of 298 K. The adsorption kinetic data indicated that the adsorption followed the pseudo-second-order kinetic model. The thermodynamic parameters, including Gibbs free energy, enthalpy, entropy, and activation energy, indicated that adsorption was spontaneous, endothermic, and was based on physisorption. The rate-limiting step was film diffusion. Based on the results, HAP-MK-GP granules could be a feasible adsorbent for the removal of dyes from industrial wastewater. Moreover, the facile granulation method presented here could be applied to other powdered adsorbents as well to prepare adsorbent granules.

- **Enhancing microstructural integrity and mechanical strength of mortar containing incinerated ash using carbon nanotube, graphene nanoplatelet and nano silica reinforcements/ Suman Kumar Adhikary, Jitendra Patel, Michael Antwi, Tuan Truong, Anshumali Mishra, Yangmei Yu, Priyadharshini Perumal. (2024) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2024.138061

  Incineration ash contains metallic aluminium that can react with cement alkalis, producing hydrogen gas, which can affect the strength of cementitious materials. In this study, we aimed to improve the technical properties of incinerated ash-based mortar using three different nanomaterials: carbon nanotubes, graphene nanoplatelets, and nano-silica. These nanomaterials were incorporated at concentrations of 0.025 wt%, 0.05 wt%, 0.1 wt%, 0.25 wt%, 0.5 wt%, and 1 wt% of the cement mass, respectively. Comprehensive analysis indicates that the type of

nanomaterials and their doses play a significant role in early age hydration, shortening the induction period and promoting the formation of C-S-H. Study results show evidence up to a 45 % enhancement in compressive strength. Sustainability assessment reveals that a dose of 0.025 % graphene nanoplatelets is the most sustainable from an environmental perspective, with approximately a 25 % improvement in compressive strength of incinerated ash mortar. Findings of the study will contribute to the understanding of nanomaterial-reinforced cementitious systems incorporating incinerated ash and offer valuable guidance for improving the performance of incinerated ash-based cementitious materials in construction applications.

- **Impact of NH4OH treatment on the ion exchange and pore characteristics of a metakaolin-based geopolymer/ Jing Li, Sarah Mailhiot, Mohammad I. M. Alzeer, Tero Luukkonen, Anu M. Kantola, Ville-Veikko Telkki, Paivo Kinnunen. (2024) RSC Advances**

  DOI: 10.1039/d4ra03972f

  We investigated the viability and influence of NH_4OH post-synthetic treatment on the pore characteristics of geopolymers. Geopolymers are a class of materials with amorphous aluminosilicate three-dimensional frameworks, regarded as amorphous analogues of zeolites. Similar to zeolites, when geopolymers are used in catalysis or adsorption applications, post-synthetic treatments such as ion exchange with NH_4^+ salts (*e.g.*, NH_4Cl and NH_4NO_3) and desilication (using strong bases such as NaOH) are necessary to introduce active sites and modify their pore structure, respectively. Recently, it has been shown that treatment with NH_4OH combines these two steps, in which acidic sites are introduced and the pore structures of zeolites are modified simultaneously. Considering the increasing interest in geopolymers in catalysis and adsorption applications, understanding the impact of such treatment on the structure of geopolymers is needed. Our diffuse reflectance infrared Fourier-transform spectra show that NH_4^+ exchanges Na^+ in the geopolymer, and laser diffraction with scanning electron microscopy images show that the particle size of the powdered geopolymer decreases after NH_4OH treatment. N_2 sorption isotherms and ^{129}Xe and ^{1}H NMR measurements revealed information about the changes in pore structures: micropores were larger than mesopores and inborn mesopores increased in diameter, thereby reducing the surface area to volume ratio. However, pore accessibility and pore connectivity were not altered by NH_4OH treatment. Since solid-state NMR and X-ray fluorescence revealed desilication, these changes in particle size and pore characteristics are considered to be due to desilication caused by NH_4OH treatment.

- **Utilization of fine concrete waste as a lightweight aggregate via granulation: Technical and environmental assessment/ Kalle Kursula, Abhijit Mistri, Mirja Illikainen, Priyadharshini Perumal. (2024) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2023.139938

  The reutilization of construction and demolition (C&D) waste alleviates the waste disposal problem and significantly reduces environmental pollution. However, fine concrete waste from various sources, such as, ready-mix plants and precast elements, is often considered a low economic value material and left for landfill. Considering a sustainable environment, material recycling should be increased in place of landfilling. The present study explores the utilization of these fine concrete wastes as aggregate material in construction via different granulation processes. The waste material used for in this study replicates the real practical situation in the construction industry. Different manufactured aggregates were characterized for their intended performance in concrete and then lightweight concrete (LWC) was made. A commercial lightweight aggregate (LWA), LECA was also considered for the characterization and concrete production by itself and combination with manufactured aggregates. Moreover, a life cycle assessment was conducted by following ISO 14040-44 guidelines to evaluate the environmental impacts within the aggregate manufacturing process as well as in concrete production. A cradle-to-gate analysis was conducted to estimate the global warming impact (GWI) and cumulative energy demand (CED) for different manufactured aggregates and finally at the concrete level. It was observed that the manufactured aggregates via the granulation process were suitable for LWC and were comparable with commercial LECA. Although the manufactured aggregates were heavier than LECA, a combination of 50% manufactured aggregate and LECA can be suggested. Moreover, the environmental impact assessment ensures the most effective granulation option for the utilization of fine C&D waste in new concrete. The calculated land conservation from utilizing C&D waste in construction shows additional benefits towards achieving sustainability.

- **Recycling high volume Fe-rich fayalite slag in blended alkali-activated materials: Effect of ladle and blast furnace slags on the fresh and hardened state properties/ Adeolu Adediran, Juho Yliniemi, Patrick N. Lemougna, Priyadharshini Perumal, Mirja Illikainen. (2023) Journal of Building Engineering**

  DOI: 10.1016/j.jobe.2022.105436

  The valorization of Fe-rich fayalite slag (FS) as a precursor for alkali-activated materials (AAMs) is hampered by its low reactivity at ambient temperature. Here, FS was blended with waste-based reactive co-binders such as ladle slag (LS) and blast furnace slag (BFS) to improve the fresh and hardened state properties of the AAMs

for potential construction applications. The results showed that the incorporation of LS and BFS as an additional source of Ca and Al accelerated the reaction kinetics and influenced the binder gel type and formation mechanism. In all the mixes, Fe, Si and Na are present in the evolving binder gel. In addition to these elements, the binder gel of the blended formulations is also rich in higher quantities of Ca and Al and showed possible formation of C-A-S-H and C-(N)-A-S-H together with the development of andradite, a calcium ferrosilicate hydrate phase formed from chemical interaction between FS and co-binders; it indicates that both FS and co-binder participated in the binder gel formation. Furthermore, the nucleating and filling effects of co-binders improved the workability, ultrasonic pulse velocity and mechanical properties; this also densified the structure and lowered the water absorption and permeable porosity of the blended mortars. The compressive strength of blended mortars was above 20 MPa, thus satisfying the strength requirements of building materials according to ASTM C62. The results of this study emphasize the reuse potential of FS with other waste streams in producing eco-friendly AAMs, which can have a wide range of construction applications.

- **Alternative alkali activator from pulp mill waste – One-part blast furnace slag mortar activated with recovery boiler fly ash/ Juho Rasmus, Katja Ohenoja, Juha Oksanen, Elijah Adesanya, Paivo Kinnunen, Mirja Illikainen. (2023) Journal of Building Engineering**

  DOI: 10.1016/j.jobe.2023.107113

  Alternative alkali activators are a growing research area in the field of alkali-activated materials (AAMs) because conventional chemical-based activators, such as sodium hydroxide and sodium silicate, have a large environmental footprint and high costs. Industrial residues are widely studied as substitutional cementitious materials in concrete and precursors in AAMs but not much as activators. In the present study, sodium rich waste from pulp mill was used as an alkali source in AAMs. Recovery boiler fly ash (RBA) is dust-like waste fraction removed from flue gases of recovery boiler by electrostatic precipitators. It consists mainly of alkalis, sulfate, and carbon while sodium sulfate is the main phase. This work utilized RBA as a sole one-part alkali activator for a precursor mixture containing 95 wt% of blast furnace slag and 5 wt% of cement, and the results were compared with two references, one without activator and the other activated with commercial sodium sulfate. The setting properties and strength gain were comparable between the RBA-activated and commercial activator-activated samples. Calorimetry data showed also similar reactivity between them, and X-ray diffractometry, thermogravimetric analysis, and scanning electron microscopy measurements revealed that the same phases were formed. The main issue was the microcracking of the paste samples when using RBA as an activator. Results confirm the earlier findings from the literature, the

activator dosage did not greatly impact the properties: in this study, the initial proportion of 1% or 3% Na_2O was the most suitable.

- **Enhancing the thermal stability of alkali-activated Fe-rich fayalite slag-based mortars by incorporating ladle and blast furnace slags: Physical, mechanical and structural changes/ Adeolu Adediran, Juho Yliniemi, Samira Moukannaa, D.D. Ramteke, Priyadharshini Perumal, Mirja Illikainen. (2023) Cement and Concrete Research**

  DOI: 10.1016/j.cemconres.2023.107098

  A proper and detailed understanding of the thermal stability of Fe-rich fayalite slag-based alkali-activated materials (AAMs) is important due to their potential use in refractory and fire-resistant applications. Here, fayalite slag (FS) was used as the main precursor for AAMs. The effects of incorporating ladle slag (LS) or blast furnace slag (BFS) and different temperature exposures up to 1000 °C were investigated through visual observation, compressive strength, ultrasonic pulse velocity (UPV), thermal conductivity, x-ray diffraction (XRD), thermogravimetry and differential scanning calorimetry (TG/DSC), Fourier transform infrared spectroscopy (FTIR) and scanning electron microscope coupled with electron probe microanalyzer (SEM-EPMA). The experimental results indicated that the incorporation of LS or BFS as additional calcium and aluminum sources positively affected the high-temperature behavior of blended mortars, which exhibited a reduction in voids, cracks, and thermal shrinkage while having higher residual strength and thermal stability than solely FS-based AAMs. This was mainly due to the differences in mineralogical transformation and the phases formed. Interestingly, the joint effect of elevated temperature exposure and the addition of LS or BFS enhanced the formation of more stable crystalline phases and densified the structure of blended mortars at 1000 °C.

- **Recycling alkali activated slag into artificial aggregate: Influence of particle size distribution of the starting material on granulation/ Kalle Kursula, Mirja Illikainen, Priyadharshini Perumal. (2023) Low-Carbon Materials and Green Construction**

  DOI: 10.1007/s44242-023-00031-5

  Wet granulation is a potential method to develop artificial aggregates. In this paper, the granulation of recycled alkali-activated slag powders with different particle size (d_{50} ranging between 12.9–127.7 μm) distributions were investigated in order to find how these affect on the engineering properties of the artificial aggregates. Blast furnace slag was added as co-binder in 10–30 wt. % during the granulation process and to enhance the properties, especially mechanical strength. The results show that

the particle size of the raw material significantly affects the engineering properties of the produced aggregates, such as the crushing force (19–131.8 N), bulk density, water absorption, porosity and microstructure of the granules. The results show that granulation is a promising method to recycle alkali-activated materials as lightweight aggregates to replace natural aggregates.

- **Optimizing activating solution and environmental leaching characteristics of Fe-rich alkali-activated Zn slag/ Vitalii Ponomar, Katja Ohenoja, Mirja Illikainen. (2023) Journal of Hazardous Materials**

  DOI: 10.1016/j.jhazmat.2022.130575

  In this work, slag from Zn processing was used to produce Fe-rich alkali-activated materials (AAMs) with low environmental impact. The interconnection between activating solution composition, compressive strength, and environmental leaching characteristics was assessed. The reaction products characterised with FT-IR, XRD, and SEM-WDS were represented by Fe-rich C-S-H gel of tobermorite-related structure. The local aggregation of Na and Mg suggests the minor role of these elements in the reaction product. The reaction product seems to be undependable on the alkali cation used in the solution. Besides, the hardening reaction took place fast, and the maximum compressive strength of 70 MPa was determined only after 1 day after mixing with silicate solutions. To decrease the economic and environmental impact, 1) simultaneous decreasing Na_2O/slag and SiO_2/slag ratios or 2) decreasing SiO_2/Na_2O ratio can be applied without prominent deterioration of the strength. Environmental leaching results showed an increase in the leached content of several metal(loid)s (e.g., As, Mo, Cr, Sb, Se, V) as a results of alkali activation, but also some immobilization effect for Ba, Pb and Zn. Also, the presence of liquid silica in the activating solutions or higher water content reduced the leaching of some elements.

- **Hydration of blended ladle slag and calcium aluminate cement/ Elijah Adesanya, Amarachi Ezu, Hoang Nguyen, Christine Ro¨ßler, Harisankar Sreenivasan, Katja Ohenoja, Paivo Kinnunen, Mirja Illikainen. (2023) Journal of Building Engineering**

  DOI: 10.1016/j.jobe.2023.105855

  Partial replacement and co-hydration of calcium aluminate cement (CAC) with ladle slag was investigated in this study as a pathway in valorizing the slag and reducing the economic cost of CAC. The impact of this replacement on the physical and microstructural properties were analysed using different techniques such as mechanical strength test, freeze-thaw, sulfate attack, XRD, SEM etc. Thermodynamic modelling was used to predict the phase assemblages of the

blended cement using the hydration kinetics of the system. Experimental results showed the reference CAC mortar and the substituted mortar exhibited comparable strength gain at 7 and 28 days, and durability as measured by sulfate attack, abrasion, and freeze-thaw resistance. A low water-to-binder ratio (0.35) lessened the effect of conversion on the hydrates, as XRD showed metastable CAH_{10} and $C_2AH_{7.5}$ as the hydrates at 7, 28 and 60 days. This however can convert later to the thermodynamically stable phase C_3AH_6. Thermodynamic modelling suggests these two metastable phases as major binding phases, while Si-hydrogarnet and FeOOH appeared a minor trace in the binder.
*Cement chemistry notation used, where C = CaO, A = Al_2O_3 and H = H_2O

- **Peracetic acid as a novel blowing agent in the direct foaming of alkali-activated materials/ M.A.H. Bhuyan, C. Kurtulus, A. Heponiemi, T. Luukkonen. (2023) Applied Clay Science**

  DOI: 10.1016/j.clay.2022.106727

  In this study, peracetic acid (PAA) was investigated as a novel blowing agent for the preparation of porous alkali-activated materials from metakaolin or blast furnace slag by the direct foaming method. PAA is an organic peroxide with lower stability of the O-O bond in comparison to H_2O_2. It also introduces acetate anions to the system, which can chelate cations to potentially increase the extent of precursor dissolution and decrease the surface tension of the gas-liquid interfaces prompting open porosity formation. PAA was compared with H_2O_2 to prepare porous alkali-activated materials by characterizing setting time, compressive strength, reaction kinetics (by isothermal calorimetry), porosity (by mercury intrusion porosimetry and helium gas pycnometry), and chemical composition (by electron probe microanalyzer, EPMA). The most significant finding was that the use of PAA caused 92%–94% and 72%–80% lower volume increase compared to H_2O_2 upon curing for metakaolin and blast furnace slag-based foams, respectively. The enhanced dissolution of the precursors when using PAA were observed from the EPMA analysis, which promoted higher compressive strength for PAA-based foams (451–537% compared to H_2O_2-based foams). There was also an indication that the use of PAA promoted the open porosity formation. As a practical implication, PAA could be well suited for applications in which the volume increase during the foam setting must be minimized.

- **Combined granulation–alkali activation–direct foaming process: A novel route to porous geopolymer granules with enhanced adsorption properties/ Yangmei Yu, Priyadharshini Perumal, Ian J. Corfe, Tirthankar Paul, Mirja Illikainen, Tero Luukkonen. (2023) Materials and Design**

DOI: 10.1016/j.matdes.2023.111781

High-value applications, such as adsorbents, have drawn attention to geopolymers. In several of those applications, having the geopolymer as porous spherical particles is beneficial. This study presents a novel process for fabricating porous metakaolin-based geopolymer granules using a combination of direct foaming, one-part alkali activation, and granulation. In short, the precursor (e.g., metakaolin) and solid activator (e.g., sodium silicate) are loaded in a granulator, in which an aqueous blowing agent (e.g., H_2O_2) is added while the granulator is running, and the obtained granules are cured at 60 °C. Characterization of the granules for physico-chemical and morphological properties indicated an increase in overall porosity, especially in the μm-scale pores. Also specific surface area (+50%) and nanoscale pore volume (+102%) increased when using more concentrated H_2O_2 (20 or 30%) compared to nonporous granules. The use of porous granules was also demonstrated in dynamic adsorption experiments for ammonium (NH_4^+) uptake, which showed up to ~126% increase in cumulative adsorption amount compared to nonporous granules. The highest NH_4^+ uptake was obtained with 10% H_2O_2 solution as the granulation fluid. The results confirmed the feasibility of the method for introducing porosity to geopolymer granules, which enhances the adsorption properties of the granules.

- **Effect of green liquor dregs as an alkali source for alkali-activated blast furnace slag mortar/ Juho Rasmus, Katja Ohenoja , Paivo Kinnunen, Mirja Illikainen. (2023) Case Studies in Construction Materials**

DOI: 10.1016/j.cscm.2023.e01950

Sodium-rich green liquor dregs (GLD) are one of the main landfilled residues generated in pulp mills, and to date, no economically profitable ways to utilise GLD has been identified. In this study, GLD have been studied to be used as an alternative alkali source together with alkali-activator, sodium metasilicate (Na_2SiO_3), for blast furnace slag (BFS) mortar. Microsilica was used as an additional silica source to ensure steady Na_2O:SiO_2-ratio (0.16). In purpose to remove the remaining organic carbon and increase the suitability of GLD to be used in alkali-activated materials, it has been first thermally treated in 525 °C. The amount of GLD in the recipes varied from 0 to 45 wt%. Calorimetry measurements showed that increasing the amount of GLD reduced the hydration heat and postponed the reaction. With thermogravimetric analysis, X-ray diffractometry and scanning electron microscopy it was found that hydrated samples with more GLD contained more carbonate phases, which indicated that the reactivity of GLD was lower in comparison with that of other raw materials. Compressive and flexural strength measurements showed that increasing the amount of GLD affected the early strength gain (2 and 7 days) of the samples, but at the age of 29 days, the

difference was not as high. The compressive strength of the reference sample at 29 days was 59 MPa, while the compressive strength of four sample recipes containing GLD (up to 36 wt%) was higher than 49 MPa. According to the results, green liquor dregs have potential to be used as a secondary alkali source in alkali-activated materials, but more detailed study should be conducted for the recipe in the future.

- **Ceramic-like membranes without sintering via alkali activation of metakaolin, blast furnace slag, or their mixture: Characterization and cation-exchange properties/ Tero Luukkonen, Elisa Olsen, Auli Turkki, Esa Muurinen. (2023) Ceramics International**

  DOI: 10.1016/j.ceramint.2022.11.252

  Alkali-activated (or geopolymer) membranes have emerged recently as an alternative for conventional ceramic membranes. Their main benefit is the simple and low-energy manufacturing not requiring sintering, and thus potential for clearly lower costs, while having largely similar performance as conventional ceramic materials. In this work, metakaolin, blast furnace slag, and their mixture (representing typical low, high, and medium Ca-content raw materials, respectively) were compared as aluminosilicate precursors for the preparation of self-supporting membrane disks (diameter 75 mm, height 3 mm). A thorough material characterization was performed to evaluate mechanical strength, shrinkage, microstructure, chemical composition, pore size distribution, specific surface area, zeta potential, and water flux at different temperatures (20–60 °C) and pressures (200–1000 kPa). Based on this screening, metakaolin-based membrane (i.e., the low-calcium system) indicated overall better performance than the two others based on blast furnace slag or their mixture. As a final part of the study, ammonium-containing model effluent ($[NH_4^+]$ = 50 mg L^{-1}) was distributed through the membrane (using 200 kPa pressure at 25 °C) to evaluate the potential for nitrogen removal and recovery. The mass balance examination indicated that ammonium was retained in the membrane matrix (i.e., not concentrated in the retentate fraction), and thus the likely removal mechanism was via ion-exchange. The obtained results provide interesting insights for the further development of alkali-activated membranes for applications requiring ammonium nitrogen removal, such as membrane bioreactors in municipal wastewater treatment.

- **Effect of material age on the adsorption capacity of low-, medium-, and high-calcium alkali-activated materials/ Johanna Laukkanen, Satu Ojala, Tero Luukkonen, Ulla Lassi. (2022) Applied Surface Science Advances**

  DOI: 10.1016/j.apsadv.2022.100345

Alkali-activated materials (AAMs) are actively studied as adsorbents in wastewater treatment. They are frequently classified as low-, medium-, or high-calcium content since the gel nanostructure of AAMs changes upon the introduction of network-modifying cations (e.g., Ca^{2+}). Furthermore, AAMs undergo changes in the phase composition and pore structure upon aging. In the present study, these two aspects were assessed for the first time in the context of adsorption: three typical mix designs involving metakaolin, blast furnace slag, or their mixture were prepared and studied for ammonium (NH_4^+) uptake at 7-, 28-, or 90-day age. The adsorption capacity of the "zeolite-like" metakaolin-based geopolymer increased from 34 to 87 mg/g when material was cured up to 90 days at room temperature. However, the adsorption capacity increase appears to be also depending on the metakaolin structure as approx. 1-month and 8-year old samples prepared with another metakaolin grade indicated almost similar adsorption capacity. Adsorption was clearly hindered when blast furnace slag was introduced in the mix designs, which turns the gel into "tobermorite-like" chain structures. Thus, this study demonstrated that using the Ca-content of precursors and material age are significant parameters for the interpretation of the adsorption results and practical development of AAM-based adsorbents.

- **Comparison of One-Part and Two-Part Alkali-Activated Metakaolin and Blast Furnace Slag/ Isabel Pol Segura, Tero Luukkonen, Juho Yliniemi, Harisankar Sreenivasan, Anne Juul Damø, Lars Skaarup Jensen, Mariana Canut, Anu M. Kantola, Ville-Veikko Telkki, Peter Arendt Jensen. (2022) Journal of Sustainable Metallurgy**

  DOI: 10.1007/s40831-022-00606-9

  One-part alkali-activated materials prepared with solid-form alkali activator are gaining attention in the construction industry, as they are an easier and safer approach for cast-in-situ applications in comparison with two-part approach (i.e., involving the use of alkali-activator solutions). The present study compares the one-part and conventional two-part mixing methods with two aluminosilicate precursors, metakaolin and ground granulated blast-furnace slag, using identical mix designs (in terms of molar ratios of SiO_2, Al_2O_3, and Na_2O) with both preparation methods. The results revealed that using one-part mix delays the setting time, increases the heat of reaction, decreases the shrinkage, and reaches between 80 and 85% of the compressive strength of the two-part mix. In addition, scanning electron microscopy, thermogravimetric analysis, and X-ray diffraction analysis showed no major differences between one- and two-part. However, energy-dispersive X-ray spectroscopy and magic angle spinning nuclear magnetic resonance experiments indicated that the extent of reaction in two-part alkali-activated mixes is higher than for one-part.

- **Oxidation of organic micropollutant surrogate functional groups with peracetic acid activated by aqueous Co(II), Cu(II), or Ag(I) and geopolymer-supported Co(II)/ Tero Luukkonen, Urs von Gunten. (2022) Water Research**

  DOI: 10.1016/j.watres.2022.118984

  Peracetic acid (PAA) in combination with transition metals has recently gained increasing attention for organic micropollutant abatement. In this study, aqueous Co(II), Cu(II), and Ag(I) were compared for their capacity to activate PAA. Co(II) outperformed Cu(II) or Ag(I) and the optimum conditions were 0.05 mM of Co(II), 0.4 mM of PAA, and pH 3. However, due to a wider applicability in water treatment, pH 7 (i.e., bicarbonate buffer) was selected for detailed investigations. The abatement of different micropollutant surrogates could be described with a second-order rate equation (observed second-order rate constants, k_{obs} were in the range of 42-132 M^{-1} s^{-1}). For the para-substituted phenols, there was a correlation between the observed second-order rate constants of the corresponding phenolates and the Hammett constants (R^2 = 0.949). In all oxidation experiments, the reaction rate decreased significantly after 1-2 min, which coincided with the depletion of PAA but also with the deactivation of the Co(II) catalyst by oxidation to Co(III) and subsequent precipitation. It was demonstrated that Co(II) immobilized on a geopolymer-foam performed approximately similarly as aqueous Co(II) but without deactivation due to Co(III) precipitation. This provides a potential option for the further development of heterogeneous catalytic Co(II)/PAA advanced oxidation processes utilizing geopolymers as a catalyst support material.

- **Ferritic calcium sulfoaluminate belite cement from metallurgical industry residues and phosphogypsum: Clinker production, scale-up, and microstructural characterization/ Visa Isteri, Katja Ohenoja, Theodore Hanein, Hajime Kinoshita, Holger Kletti, Christiane Rößler, Pekka Tanskanen, Mirja Illikainen, Timo Fabritius. (2022) Cement and Concrete Research**

  DOI: 10.1016/j.cemconres.2022.106715

  The production of ferrite-rich calcium sulfoaluminate belite (CSABF) cement clinker, also containing MgO, from ladle slag, Fe-slag, and phosphogypsum was translated from a lab-scale to a pilot demonstration in a 7-metre kiln at 1260 °C. An account of the pilot trials/manufacturing is presented, and the process was robust. Laboratory tests prior to scale-up showed that gehlenite formation can be inhibited in the CSABF clinker by adding excess CaO in the raw meal; however, this reduces the amount of iron (Fe) that can be incorporated into ye'elimite and leads to higher ferrite (C_6AF_2) content. Detailed microstructural analyses were performed on the clinker to reveal the clinker composition as well as the partition of the minor elements. Different ferrite

phases with varying amounts of titanium and iron are distinguished. Eighty-five percent of the clinker raw meal was comprised of side-stream materials and the clinker produced in the kiln had chemical raw-material CO_2 emissions 90% lower than that of Portland cement made from virgin raw materials. These results can have a significant impact in regions with a prospering metallurgical industry, enabling industrial decarbonisation and resource efficiency.

- **Improved strength development and frost resistance of Portland cement ground-granulated blast furnace slag binary binder cured at 0 ◦C with the addition of calcium silicate hydrate seeds/ Ahmad Alzaza, Katja Ohenoja, Mirja Illikainen. (2022) Journal of Building Engineering**

  DOI: 10.1016/j.jobe.2021.103904

  Low ambient temperatures drastically decelerate the strength development of cementitious materials, which shortens the construction season in cold regions. The use of ground-granulated blast furnace slag (GGBFS) in concreting works is usually avoided in winter because of its slower hydration rate relative to Portland cement (PC). In this study, the impacts of calcium silicate hydrate (C-S-H) seeds on the strength development and reaction rate of PC/GGBFS binders cured at 0 °C were investigated. The results showed that the addition of C-S-H seeds can efficiently compensate for the strength loss caused by replacing PC with GGBFS, and this effect is more obvious at a lower GGBFS content (30%) than at a high content (50%). Better frost resistance was gained in the seeded binder containing 30% GGBFS than in the pure PC binder. The enhanced compressive strength and frost resistance in the seeded binary binder were attributed to the accelerated PC reaction rate, enhanced pozzolanic reaction rate and degree of GGBFS, and increased amount of pore-filling hydration products due to the nucleation effect of the C-S-H seeds.

- **Fusion of phosphate by-products and glass waste for preparation of alkali-activated binders/ Samira Moukannaa, Abdelilah Aboulayt, Rachid Hakkou, Mostafa Benzaazoua , Katja Ohenoja, Angel Palomo, Ana Fernández-Jimenez. (2022) Composites Part B: Engineering**

  DOI: 10.1016/j.compositesb.2022.110044

  Landfilling of mine and industrial waste streams leads to environmental and economic issues. Sustainable management methods through valorization in manufacturing green construction materials are a current research interest. Here, a promising process for recycling mine tailings, such as phosphate sludge, is proposed. A mixture of phosphate sludge, kaolin clay (Al source), and glass waste (Si source) was prepared. Three fluxing agents were tested at 1000 °C (NaOH, Na_2CO_3, Na_2SO_4).

Na_2CO_3 was selected as the most cost-effective. The precursors were alkaline activated with NaOH solution (2, 6, and 8 M). At 28 days of curing (20 h room temperature + 6 h 85 °C + room temperature), the best compressive strength (of more than 45 MPa) was obtained with 8 M NaOH. The reaction products, characterized by XRD, FTIR, SEM, and MAS NMR, show that the main reaction products is a gel N–A–S–H/(N,C)–A–S–H together with some unreacted crystalline phases formed during the fusion.

- **Blending eco-efficient calcium sulfoaluminate belite ferrite cement to enhance the physico–mechanical properties of Portland cement paste cured in refrigerated and natural winter conditions/ Ahmad Alzaza, Katja Ohenoja, Visa Isteri, Theodore Hanein, Daniel Geddes, Minna Poikelispää, Mirja Illikainen. (2022) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2022.104469

  The acceleration impacts of calcium sulfoaluminate belite ferrite (CSABF)—a cement produced from industrial side streams—on the hydration and strength development of Portland cement (PC) paste cured at −5 °C with and without pre-curing at room temperature were investigated. The impacts of eco-friendly CSABF cement content and pre-curing on the setting time and hardened properties of pastes were investigated. Freezing point of the paste and the amount of freezable water (FW) decreased with CSABF cement content and pre-curing. Hydration rate increased with CSABF cement content. By adding an optimal CSABF cement content, the compressive strength of paste cured at −5 °C increased by 500%. The effects of pre-curing on the compressive strength of the subzero-cured pastes were highly dependent on CSABF cement content and curing period. After 6 months, the outdoor-cured 70%PC/30%CSABF paste gained compressive strength comparable to that in the 90-day-old pair cured at −5 °C and continuous strength gain was detected up to one-year. The microstructural observations and porosity results are consistent with compressive strength measurements.

- **Mechanical and durability properties of C–S–H-seeded cement mortar cured at fluctuating low temperatures with granulated blast furnace slag as fine aggregates/ Ahmad Alzaza, Katja Ohenoja, Faiz Uddin Ahmed Shaikh, Mirja Illikainen. (2022) Journal of Building Engineering**

  DOI: 10.1016/j.jobe.2022.104879

  The conservation of natural resources, efficient use of industrial side-streams, and reduction of environmental impacts are the main targets of the construction sector worldwide. However, the low ambient temperatures and long harsh winter seasons in northern regions limit the use of industrial side-streams in construction activities

under cold weather conditions due to their slow strength development rate. This study aimed to develop an eco-friendly construction material suitable for construction under cold weather conditions using blast furnace slag as a binder and fine aggregate admixed with a calcium silicate hydrate seed accelerator in mortar. Natural sand (NS) was volumetrically substituted with 25%, 50%, 75%, and 100% of granulated blast furnace slag (GBFS) fine aggregate in mortar cured at fluctuating low/freezing temperatures (+5 to −5 °C), representing the late fall and early spring seasons in northern regions. The mortar's compressive strength increased with the incorporation of GBFS aggregate over the first three days of curing and decreased thereafter. A denser interfacial transition zone was captured around GBFS aggregates than NS in the three days old mortars. The deceleration influences of fluctuating low/freezing temperatures on the compressive strength development of mortars were diminished with time. Capillary water absorption increased with higher GBFS aggregate contents. Mortar with 25–50 vol.% GBFS aggregates exhibited greater frost resistance than control mortar with NS only. The incorporation of GBFS aggregate enhanced the mortar's resistance against a sulfuric acid attack. This study demonstrates the potential of GBFS aggregate for use in construction under cold weather conditions.

- **Recycling of Precast Concrete Waste Sludge With Paper Mill and Biomass Ashes for Lightweight Granulated Aggregate Production/ Samira Moukannaa, Kalle Kursula, Priyadharshini Perumal, Katja Ohenoja, Mirja Illikainen. (2022) Frontiers in Materials**

  DOI: 10.3389/fmats.2022.877160

  The construction and demolition waste generation is increasingly evolving with the rapid urbanization, with more than a quarter of the produced waste being landfilled without further treatment or recycling strategy. Hence, sustainable management and valorization methods such as recycling in construction materials is becoming increasingly essential to tackle the economic and environmental burdens of landfilling waste. Construction and demolition waste recycling has been intensively studied. However, the present study proposes a promising solution for recycling construction and demolition wastes (CDWs) from the precast concrete waste sludge and ashes from paper mill sludge and biomass. Artificial lightweight aggregates were designed and produced by alkali activating a mixture of 50–90 wt% of dried and milled CDW with 3–25 wt% of ash and 5–35 wt% of blast furnace slag. The properties of the produced aggregates were assessed *via* density, water absorption, porosity, and crushing tests, in addition to microstructural characterizations using XRD and scanning electron microscopy SEM analysis. The optimum NaOH concentration was 8M with the highest mechanical properties and lowest efflorescence. The produced aggregates revealed a high crushing force of 82 N at 28 days with 50 wt% CDW,

15 wt% biomass ash, and 25 wt% blast furnace slag presenting a possible recycling pathway for such side-stream materials.

- **Durability of alkali-activated Fe-rich fayalite slag-based mortars subjected to different environmental conditions/ Adeolu Adediran, Juho Yliniemi, Valter Carvelli, Elijah Adesanya, Mirja Illikainen. (2022) Cement and Concrete Research**

  DOI: 10.1016/j.cemconres.2022.106984

  Fe-rich alkali activated materials (AAMs) require detailed understanding of their durability prior to their real-life application in the construction industry. Three mixes were formulated with fayalite slag (FS) as the main precursor. The effect of incorporation of ladle slag (LS) or blast furnace slag (BFS) on the shrinkage and exposure to physical and chemical attacks representing environmental conditions in cold and tropical regions (acidic solution at room temperature and in freeze-thaw, combined sodium sulfate and sodium chloride solution at room temperature and in freeze-thaw, freeze-thaw in water and dry-wet cycles) was investigated via visual observation, mass loss, compressive strength, X-ray diffraction (XRD), mercury intrusion porosimetry (MIP), and scanning electron microscope coupled with energy dispersive X-ray spectroscopy (SEM-EDS). Experimental results show the considerable role of incorporated LS and BFS in modifying the gels formed and controlling material degradation of blended AAMs after exposure. In contrast, sole FS-based samples were completely degraded particularly those exposed to freeze-thaw in water, acid, and combined sodium sulfate and sodium chloride solution, indicating their vulnerability to frost and chemical attacks.

- **Fly ash geopolymer as a coating material for controlled-release fertilizer based on granulated urea/ Rashidah Mohamed Hamidi, Ahmer Ali Siyal, Tero Luukkonen, Rashid M. Shamsuddin, Muhammad Moniruzzaman. (2022) RSC Advances**

  DOI: 10.1039/d2ra06056f

  Nitrogen loss from urea fertiliser due to its high solubility characteristics has led to the invention of controlled release urea (CRU). Majority of existing CRU coatings are produced from a non-biodegradable, toxic and expensive synthetic polymers. This study determines the feasibility of fly ash-based geopolymer as a coating material for urea fertilizer. The effects of fly ash particle size (15.2 μm, 12.0 μm, and 8.6 μm) and solid to liquid (S : L) ratio (3 : 1, 2.8 : 1, 2.6 : 1, 2.4 : 1 and 2.2 : 1) on the geopolymer coating, the characterization such as FTIR analysis, XRD analysis, surface area and pore size analysis, setting time analysis, coating thickness, and crushing strength, and the release kinetics of geopolymer coated urea in water and soil were

determined. Lower S : L ratio was beneficial in terms of workability, but it had an adverse impact on geopolymer properties where it increased porosity and decreased mechanical strength to an undesirable level for the CRU application. Geopolymer coated urea prepared from the finest fly ash fraction and lowest S : L ratio demonstrated high mechanical strength and slower urea release profile. Complete urea release was obtained in 132 minutes in water and 15 days in soil from geopolymer-coated urea whereas for uncoated urea it took only 20 minutes in water and 3 days in soil. Thus, geopolymer can potentially be used as a coating material for urea fertilizer to replace commonly used expensive and biodegradable polymer-based coatings.

- **Enhancing the hardened properties of blended cement paste cured at 0 °C by using alkali-treated ground granulated blast furnace slag/ Ahmad Alzaza, Katja Ohenoja, Rawia Dabbebi, Mirja Illikainen. (2022) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2022.104757

  The use of high-volume ground granulated blast furnace slag (GGBFS) in cement-based materials significantly reduces CO_2 emissions. Nevertheless, low curing temperatures are barriers to using environmentally friendly materials in winter construction works. This is mainly attributed to slow GGBFS's reactivity and blends' strength development due to the low alkalinity offered by the slow hydration rate of Portland cement (PC) at low temperatures. In this study, sodium hydroxide was employed to produce dry reactive pre-alkali-activated GGBFS (A-GGBFS), with an intention to increase the system's alkalinity and reactivity. The blended cement paste was prepared with 50% PC replacement with untreated and treated GGBFS, and cured constantly at 0 °C for 28 days. The A-GGBFS accelerated the hydration rate and enhanced the precipitation of hydration products. By adding an optimal NaOH content during the pre-alkali-activation process, the 3 and 28 days compressive strengths of paste increased by 41% and 37%, respectively, gaining a comparable 28 days compressive strength to that measured in a 100% PC-based binder. The microstructural assessments are consistent with compressive strength measurements.

- **Characterization of an aged alkali-activated slag roof tile after 30 years of exposure to Northern Scandinavian weather/ Tero Luukkonen, Juho Yliniemi, Brant Walkley, Daniel Geddes, Ben Griffith, John V. Hanna, John L. Provis, Paivo Kinnunen, Mirja Illikainen. (2022) RSC Advances**

  DOI: 10.1039/d2ra04456k

Alkali-activated materials (AAMs) have been known as an alternative cementitious binder in construction for more than 120 years. Several buildings utilizing AAMs were realized in Europe in the 1950s–1980s. During the last 30 years, the interest towards AAMs has been reinvigorated due to the potentially lower CO_2 footprint in comparison to Portland cement. However, one often-raised issue with AAMs is the lack of long-term studies concerning durability in realistic conditions. In the present study, we examined a roof tile, which was prepared from alkali-activated blast furnace slag mortar and exposed to harsh Northern Scandinavian weather conditions in Turku, Finland, for approximately 30 years. Characterization of this roof tile provides unique and crucial information about the changes occurring during AAM lifetime. The results obtained with a suite of analytical techniques indicate that the roof tile had maintained excellent durability properties with little sign of structural disintegration in real-life living lab conditions, and thus provide in part assurance that AAM-based binders can be safely adopted in harsh climates. The phase assemblage and nanostructural characterization results reported here further elucidate the long-term changes occurring in AAMs and provide reference points for accelerated durability tests and thermodynamic modelling.

- **In situ remediation of metal(loid)-contaminated lake sediments with alkali-activated blast furnace slag granule amendment: A field experiment/ Johanna Laukkanen, Esther Takaluoma, Hanna Runtti, Jari Mäkinen, Tommi Kauppila, Seppo Hellsten, Tero Luukkonen, Ulla Lassi. (2022) Journal of Soils and Sediments**

  DOI: 10.1007/s11368-022-03140-z

  Purpose Adsorbent amendment to contaminated sediments is one in situ remediation method to decrease the bioaccessibility of pollutants from the sediments. In this work, alkali-activated blast furnace slag (BFS) granules were used in a field experiment at Lake Kivijärvi (Finland). The lake was heavily affected by a mining accident in 2012, which released a significant peak load of metals and sulfate. The purpose of this work was to evaluate the performance of the novel amendment material for in situ remediation in real conditions with a preliminary cost estimation. Methods Alkali-activated BFS granules were prepared and characterized for composition, microstructure, and surface properties. Two mesocosms were placed in the lake: one with granule dosing and another without. Sediment and pore water samples were collected after a two-week period. Similar small-scale experiment was performed in laboratory with a threemonth duration. Bioaccessibility of metals from sediments was assessed with a three-stage leaching procedure. Results The granules were effective in decreasing the mobility of Fe, Zn, Ni, and Cr in all leaching stages by approximately 50–90% in comparison with unamended sediment in the mesocosm experiment. Laboratory-scale incubation experiments also indicated decreased release of Ba, Co, Ni, Al, Fe, Mg, Mn and S. The estimated material costs were lower than the removal

of the contaminated sediments with dredging and off-site treatment. Conclusion The results showed preliminarily the effectiveness of alkaline-activated BFS in the remediation of metal-contaminated sediments in a field experiment. However, topics requiring further study are the leaching of trace elements from the material and impact on the sediment pH.

- **Water disinfection with geopolymer–bentonite composite foam containing silver nanoparticles/ Tero Luukkonen, Mohammad Bhuyan, Anna-Maria Hokajärvi, Tarja Pitkänen, Ilkka T. Miettinen. (2022) Materials Letters**

  DOI: 10.1016/j.matlet.2021.131636

  Geopolymers resemble conventional ceramics but can be manufactured at near-ambient temperatures. In this work, geopolymer–bentonite composite foam with silver nanoparticles was prepared and applied for water disinfection, inspired by point-of-use ceramic water filters. The inactivation efficiency against *Escherichia coli* and intestinal enterococci bacteria was found to be promising (0.6–2.4 and 0.3–1.4 $\log_{10}$ reductions, respectively) for ~1 d. However, the inactivation efficiency against somatic coliphage viruses was poor (<0.05 $\log_{10}$). The geopolymer matrix did not alter the chemical water quality. Thus, the pH and the concentrations of Ag, Si, Al, and Na remained in compliance with drinking water guideline values, and the foam showed no physical disintegration. These results provide preliminary proof of concept of the suitability of geopolymer foam composites for point-of-use water disinfection.

- **Low-temperature (−10 °C) curing of Portland cement paste – Synergetic effects of chloride-free antifreeze admixture, C–S–H seeds, and room-temperature pre-curing/ Ahmad Alzaza, Katja Ohenoja, Isak Langås, Bård Arntsen, Minna Poikelispää, Mirja Illikainen. (2022) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2021.104319

  Cold weather drastically shortens the construction season in northern regions. Low ambient temperatures are known to have detrimental impacts on the reactivity and hardened performance of cementitious materials. This study therefore aims to assess the combined impacts of calcium silicate hydrate (C–S–H) seeds, binary chloride-free antifreeze admixture (i.e., urea and calcium nitrate), and short-period precuring at room temperature (23 ± 1 °C) on ordinary Portland cement (OPC) paste-cured at −10 °C. The heat of hydration, setting time, compressive strength, freezing point, frozen water amount, hydration products precipitation rate, water absorption, and permeable porosity were investigated experimentally. The best results in terms of compressive strength, degree of hydration, water absorption, and permeable porosity were obtained when C–S–H seeds, antifreeze admixture, and precuring were combined due to their mutual impacts. In the absence of room-temperature precuring, C–S–H

seeds additive and antifreeze admixture showed negligible acceleration impacts on compressive strength development of subzero-cured paste. The incorporation of seeds and antifreeze admixture decreased the freezing points of the binders and thus protected the admixed binders against frost damage, and their effects were more obvious when combined with a few hours of precuring. The compressive strength of 28 d-old OPC paste modified by C–S–H seeds and antifreeze admixture and treated with precuring developed rapidly at −10 °C, gaining 96% (75.1 MPa) of that measured in control paste cured at room temperature (78 MPa), with comparable durability properties and a significant reduction of energy consumption and CO_2 emissions.

- **High-temperature performance of slag-based Fe-rich alkali-activated materials/ Vitalii Ponomar, Elijah Adesanya, Katja Ohenoja, Mirja Illikainen. (2022) Cement and Concrete Research**

  DOI: 10.1016/j.cemconres.2022.106960

  Fe-rich alkali-activated materials have been studied for their suitability for high-temperature application up to 1000 °C. The evolution of compressive strength, mineral composition and microstructure was monitored using FT-IR, XRD, TGA and SEM-WDS for the pastes and mortars obtained by alkali activation of fayalite and wüstite non-ferrous slags. For both binders, the changes in compressive strength revealed moderate fluctuations below 400 °C due to water evaporation, a sharp drop in strength to 25 MPa at 600 °C due to collapse of the original gel structure, and reinforcement of the strength above 600 °C due to sintering densification and formation of gehlenite-åkermanite or diopside-albite ceramic. An extensive reaction of the quartz aggregate with a sodium-rich binder resulted in the formation of an iron silicate phase that contributed to a further increase in the strength up to 70 MPa by increasing both temperature and time of heating.

- **Investigation of different paper mill ashes as potential supplementary cementitious materials/ Samira Moukannaa, Mohammad Alzeer, D.D. Ramteke, Katja Ohenoja, Juha Roppo, Paivo Kinnunen, Mirja Illikainen. (2022) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2022.132583

  Integrating supplementary cementitious materials (SCMs) in cement-based construction materials is a key strategy for reducing environmental burdens and the greenhouse gas emissions related to cement production. Supplies of commonly applied SCMs such as fly ash and blast furnace slag are becoming limited, and therefore the search for alternative SCMs is of high significance. The present research investigates the viability of four paper mill ashes collected at different stages from the same incineration process as SCMs at different cement substitution rates

(5–30 wt%). The ashes were first classified depending on their mineralogical and chemical composition, and their contribution to strength development of the prepared mortars is examined. Furthermore, the effects of the ashes on the hydration kinetics and the fresh and hardened properties of the prepared mortars were studied. The obtained results showed that a high level of SCM replacement accelerates the early hydration reactions and decreases the setting time. In addition, the incorporation of paper mill ashes increased the bound water depending on the ash type and resulted in strength development of the mortars at low replacement per- centages (5–10 wt%). This study shows that the ashes belonging to type C medium acid based on bio ash classification could be incorporated as SCMs at a maximum level of 10 wt%, while those corresponding to type C low acid could be used up to 20–30 wt%.

- **Production of artificial aggregates by granulation and carbonation of recycled concrete fines/ Kalle Kursula, Priyadharshini Perumal, Katja Ohenoja, Mirja Illikainen. (2022) Journal of Material Cycles and Waste Management**

  DOI: 10.1007/s10163-022-01457-y

  There is a growing need to find ways to reuse fine concrete waste from the construction industry. In this study, recycled concrete fines were granulated and used as lightweight aggregates. Ladle slag, a steel industry residue, was used as a cobinder in different ratios (0, 10, 20, and 30%). The materials were blended and granulated, and then the granules were cured in three conditions: ambient condition, humidity chamber, and carbonation chamber. The results showed that the ladle slag content of 30% cured in a humidity chamber produced the strongest granules, with a crushing strength of 127 N, which was 135% greater than a commercial lightweight aggregate. The granules generally had satisfactory density and water absorption with a higher ladle slag content. Carbonation increased the granule strength with a low ladle slag content and decreased the granules' water absorption. The improved physical and mechanical properties of carbonated granules are attributed to the formation of calcium carbonate during the carbonation process. The granules produced in this study show good potential for use as lightweight aggregates in the construction industry.

- **High strength fiber reinforced one-part alkali activated slag composites from industrial side streams/ Priyadharshini Perumal, Hoang Nguyen, Valter Carvelli, Paivo Kinnunen, Mirja Illikainen. (2022) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2021.126124

  This paper details the effect of fiber reinforcement on mechanical characteristics of by-products based one-part alkali activated material (AAM). Two different binder

matrices were considered in this study, such as, plain slag, and ternary blended slag, to understand their efficiency in fiber reinforced system. These matrices were reinforced with 1% v/v of three different fibers (steel, glass and basalt) to improve the flexural performance of high strength mortar blends. Steel fiber reinforced one-part AAM outperforms mineral fibers in compressive strength contribution. The fracture energy of steel fiber reinforced compositions was roughly 4 times higher than that of mineral fiber reinforced materials. In addition, the flexural performance of ternary blended matrix was higher than that of slag-based composition regardless fiber types and properties. Finally, preliminary finite element modelling was considered to assess the applicability of the concrete damage plasticity constitutive model in predicting the nonlinear behavior of the developed composites. The numerical predictions proved the accuracy of the model with good agreement between experimental and numerical results.

- **Valorizing (cleaned) sulfidic mine waste as a resource for construction materials/ Jillian Helser, Priyadharshini Perumal, Valérie Cappuyns. (2022) Journal of Environmental Management**

  DOI: 10.1016/j.jenvman.2022.115742

  Proper management and storage of mine waste, e.g., tailings and waste rock, is one of the main issues that mining industries face. Additionally, there is already an uncountable amount of existent historical mine waste, which may, even centuries after the closure of the mine, still be leaching contaminants into the environment. One solution to minimize the risks associated with the mine waste, with also potential economic benefits, is through the valorization of the waste. This can be done by first recovering valuable metals and removing hazardous contaminants. Then, the remaining residue can be valorized into green construction materials, such as geopolymers, ceramics or cement. For some mine waste materials, such as those with only trace levels of metals that are not economically viable to extract, the “waste” can be reused directly without this additional cleaning step. In the present study, mine waste originating from three different sites was characterized and compared with the cleaned mine waste (i.e., cleaned by bioleaching or flotation methods) and with different types of green construction materials containing 13–80 wt% (cleaned and uncleaned) mine waste. Particular emphasis was given to the mobilization of metal(loid)s from the mine waste and construction materials (i.e., ceramics, alkali-activated materials and cement) under different conditions, through a series of leaching tests (i.e., EN 12457–2, US EPA's Toxicity Characteristic Leaching Procedure, and a pH-dependent leaching test). The leaching tests were applied to either mimic current ‘natural’ conditions at the mining site, conditions in a landfill (end of life) or extreme conditions (i.e., extremely acidic or alkaline pH). Most of the original mine waste samples contain high levels of Pb (18–3160 mg/kg), Zn (66–10500 mg/kg), and As (10–4620 mg/kg). . The cleaning

methods were not always efficient in removing the metal(loid)s and sulfur. In some cases, the cleaned mine waste samples even contained higher total metal(loid) and sulfur concentrations than the original mine waste samples. Based on the leaching studies, some alkali-activated materials, ceramics, and cement effectively immobilized certain metals (e.g., <0.5 mg/kg of Pb and <4 mg/kg of Zn). Also, longer curing times of the alkali-activated materials, in most cases, improved the immobilization of metal(loid)s. Additionally, for ceramics, the temperature at which the test pieces were fired (up to 1060 °C), also played a major role in decreasing the mobility of some metal(loid)s, while increasing others (e.g., As, potentially via the structural rearrangement of As and Fe). Overall, through this detailed characterization, the environmental impact from the mine waste to the downstream products was evaluated, determining which valorization methods are the most viable to close the circular economy loop.

- **Using recycled aggregate concrete at a precast-concrete plant: A multi-criteria company-oriented feasibility study/ Víctor Revilla-Cuesta, Francisco Fiol, Priyadharshini Perumal, Vanesa Ortega-Lopez, Juan M. Manso. (2022) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2022.133873

  Numerous test results at laboratory scale confirm the utility of Recycled Aggregate (RA) for the development of concrete that demonstrates durability and adequate in-fresh and mechanical behavior. However, feasibility evaluations of the use of RA in real industrial applications are necessary, before any large-scale industrial application of these products can begin. In this research, the feasibility of producing precast-concrete components containing large amounts of coarse RA at a precast-concrete plant is analyzed. Two Self-Compacting Concretes (SCC) were produced incorporating 0% and 100% coarse RA, respectively, at both laboratory scale (0.08 m^3) and industrial scale (2 m^3). Work took place at the industrial-scale facilities of a precast-concrete company that was collaborating in this study. Flowability and mechanical behavior were maintained as concrete production volumes increased, and concrete strength even increased after adding coarse RA, due to a careful mix design. However, the durability performance worsened by around 20% when produced at industrial scale, being this worsening higher whether coarse RA was used. A Multi-Criteria Decision-Making (MCDM) analysis, in which the criteria of the precast-concrete company defined the relative importance of each concrete property, showed the feasibility of manufacturing precast-SCC components containing coarse RA for interior usage, whose fundamental requirement is adequate mechanical strength. The results of the MCDM analysis also underlined the lower cost of coarse RA, making its use in SCC components cast with large concrete volumes advisable. Overall, the addition of coarse RA in the precast-concrete industry is recommended in the interests of a greener construction sector.

- **Potential of Mechanochemically Activated Sulfidic Mining Waste Rock for Alkali Activation/ He Niu, Lugas Raka Adrianto, Alexandra Gomez Escobar, Vladimir Zhukov, Priyadharshini Perumal, Janne Kauppi, Paivo Kinnunen, Mirja Illikainen. (2021) Journal of Sustainable Metallurgy**

  DOI: 10.1007/s40831-021-00466-9

  Sulfidic mining waste rock is a side stream from the mining industry with a potential environmental burden. Alkali activation is a promising method for transforming mining waste into construction materials. However, the low reactivity of minerals can be a sizeable challenge in alkali activation. In the present study, the reactivity of waste rock was enhanced by mechanochemical treatment with a LiCl-containing grinding aid. X-ray diffraction (XRD) and diffuse reflectance infrared Fourier transform (DRIFT) analysis were utilized to display the structural alteration of individual minerals. A schematic implication of the grinding mechanism of mica was provided according to the results of transmission electron microscopy (TEM) and scanning electron microscopy (SEM). The alkaline solubility displayed the enhanced chemical reactivity of the waste rock, in which Si and Al solubility increased by roughly 10 times and 40 times, respectively. The amorphization of aluminosilicate is achieved through chemical assisted mechanochemical activation. Sulfidic waste rock, as the sole precursor in alkali activation, achieved a 28-day compressive strength exceeding 10 MPa under ambient curing conditions. The simulation of the upscaled grinding process was conducted via the HSC Chemistry® software with a life-cycle assessment. The results showed that mining waste rock can be a promising candidate for geopolymer production with a lower carbon footprint, compared to traditional Portland cement.

- **The Effect of Fluoride and Iron Content on the Clinkering of Alite-Ye'elimite-Ferrite (AYF) Cement Systems/ Visa Isteri, Katja Ohenoja, Theodore Hanein, Hajime Kinoshita, Mirja Illikainen, Pekka Tanskanen, Timo Fabritius. (2021) Frontiers in Built Environment**

  DOI: 10.3389/fbuil.2021.698830

  Alite–ye'elimite–ferrite (AYF) cement is a more sustainable alternative to Portland cement (PC) that may offer improved mechanical, rheological, and chemical performance. Using traditional raw materials and conventional clinker processing conditions, alite (C_3S) and ye'elimite ($C_4A_3\$$), the major phases in PC and calcium sulfoaluminate (CSA) cements, respectively, cannot be coproduced. The typical formation temperature in the kiln for alite is >1350°C, but ye'elimite normally breaks down above 1300°C. However, with careful composition control and in the presence of fluoride, alite can be mineralized and formed at lower temperatures, thus enabling

the production of AYF clinkers in a single stage. In this study, the production of AYF cement clinkers with different chemical compositions is attempted at 1250°C. The sensitivity of the fluoride content is initially assessed with a fixed target clinker composition to determine the optimal requirements. The effect of altering the target ferrite (C_4AF) and alite (C_3S) contents is also assessed followed by the effect of altering the target C_4AF and $C_4A_3\$$ contents. It is shown that AYF clinkers can be produced in a single stage through the careful control of the fluoride content in the mix; however, the formation/persistence of belite and mayenite could not be avoided under the conditions tested. It is also shown that ~10 wt% ferrite in the target composition provides sufficient AYF clinker burnability and the amount of fluoride needs to be controlled to avoid stabilization of mayenite.

- **Effect of organic resin in glass wool waste and curing temperature on the synthesis and properties of alkali-activated pastes/ Patrick N. Lemougna, Adeolu Adediran, Juho Yliniemi, Tero Luukkonen, Mirja Illikaine n. (2021) Materials and Design**

  DOI: 10.1016/j.matdes.2021.110287

  This study investigated the effect of organic resin contained in glass wool on synthesis of alkali-activated binders. The study was performed on glass wool containing sugar or phenolic resin, comparing it with glass wool that did not contain resin, as a reference. The results showed that the organic resin could be qualitatively identified using Fourier-transform infrared spectroscopy (FTIR) and thermo gravimetry-mass spectrometer (TG-MS), with gradual decomposition occurring between 200 °C and 550 °C. The presence of organic resin reduced the milling efficiency of glass wool, modified the rheology by increasing the liquid demand, and slowed the strength development at room temperature. However, interestingly, the effect of the resin on the strength of the paste was less obvious at an age of 28 days. Curing for 24 h at 40 °C was beneficial for one-day strength development, in comparison to 20 °C and 60 °C, independent of the presence of the resin. All the cured paste samples, with and without resin, achieved a compressive strength of more than 40 MPa at 28 days, satisfying the requirement for many structural applications. Nevertheless, water immersion affected the materials' strength, suggesting their suitability for dry environments or the need for suitable co-binders to increase their durability and water resistance.

- **Boosting the performance of electric double layer capacitor via engaging pectin macromolecular electrolyte with elevated ionic conductivity and potential window stability/ P. Perumal, P. Christopher Selvin. (2021) Chemical Engineering Journal Advances**

  DOI: 10.1016/j.ceja.2021.100178

Biopolymer solid electrolytes (BSEs) are emerged recently as a core part of research towards the numerous electrical appliances at the same time pushes forward to the implementation of greener solid state electrochemistry devices as well as practical promotions. Development of Li^+ conducting pectin electrolytes is considered for the solid state electric double layer capacitor (EDLC) application for the first time and synthesized via solution casting approach. The performance of pectin electrolytes have been characterized by XRD, FTIR, FESEM, AC impedance, LSV, EIS and CV analysis. The obtained pectin electrolytes shows the significant conductivity of 3.44×10^{-3} Scm^{-1} for the additive and pectin ratio of 30 (m.wt%) pectin: 70 (m.wt%) LiBr. The same complex demonstrates the window stability of 3.78 V. Evidently, this optimal pectin: LiBr is recommended for fabrication of solid state EDLC and manifests the electrochemical capacitance of 19.04 F/g with excellent reversible performance. Based on these promising results, research on bio-macromolecular electrolytes is an advanced platform for designing robust energy storage devices especially wearable and flexible kinds.

- **Enhancing the hardened properties of blended cement paste cured at 0 °C by using alkali-treated ground granulated blast furnace slag/ Ahmad Alzaza, Katja Ohenoja, Rawia Dabbebi, Mirja Illikainen. (2021) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2021.104128

  The use of high-volume ground granulated blast furnace slag (GGBFS) in cement-based materials significantly reduces CO_2 emissions. Nevertheless, low curing temperatures are barriers to using environmentally friendly materials in winter construction works. This is mainly attributed to slow GGBFS's reactivity and blends' strength development due to the low alkalinity offered by the slow hydration rate of Portland cement (PC) at low temperatures. In this study, sodium hydroxide was employed to produce dry reactive pre-alkali-activated GGBFS (A-GGBFS), with an intention to increase the system's alkalinity and reactivity. The blended cement paste was prepared with 50% PC replacement with untreated and treated GGBFS, and cured constantly at 0 °C for 28 days. The A-GGBFS accelerated the hydration rate and enhanced the precipitation of hydration products. By adding an optimal NaOH content during the pre-alkali-activation process, the 3 and 28 days compressive strengths of paste increased by 41% and 37%, respectively, gaining a comparable 28 days compressive strength to that measured in a 100% PC-based binder. The microstructural assessments are consistent with compressive strength measurements.

- **Antibacterial Properties and Cytotoxicity of 100% Waste Derived Alkali Activated Materials: Slags and Stone Wool-Based Binders/ Caterina Sgarlata, Giovanni Dal Poggetto, Federica Piccolo, Michelina Catauro, Katja Traven, Mark Češnovar, Hoang Nguyen, Juho Yliniemi, Luisa Barbieri, Vilma Ducman, Isabella Lancellotti, Cristina Leonelli. (2021) Frontiers in Materials**

  DOI: 10.3389/fmats.2021.689290

  In this study we compare the leaching behavior and the antibacterial and cytotoxic properties of 100% slag or stone wool derived alkali activated materials. The antibacterial activity was measured as the inhibiting capacity against two Gram-negative bacterial strains, *Escherichia coli* and *Pseudomonas aeruginosa* and one Gram-positive bacterial strain: *Enterococcus faecalis*. The cytotoxicity properties were tested on mouse embryonic fibroblast NIH-3T3 cell-line. It was proved that the high quality of the 3D aluminosilicate network of the consolidated materials obtained from powders of CaO or MgO-rich slags or stone wool, opportunely activated with NaO and/or Na-silicate, was capable of stabilizing heavy metal cations. The concentrations of leachate heavy cations were lower than the European law limit when tested in water. The effect of additives in the composites, basal fibers or nanocellulose, did not reduce the chemical stability and slightly influenced the compressive strength. Weight loss in water increased by 20% with basalt fibers addition, while it remained almost constant when nanocellulose was added. All the consolidated materials, cement-like in appearance, exhibited limited antibacterial properties (viability from 50 to 80% depending on the bacterial colony and the amount of sample) and absence of cytotoxicity, envisaging good acceptance from part of the final consumer and zero ecological impact. CaO-rich formulations can replace ordinary Portland cement (showing bacterial viability at 100%) with a certain capability for preventing the reproduction of the *E. coli* and *S. aureus* bacteria with health and environmental protection results.

- **Evidence of formation of an amorphous magnesium silicate (AMS) phase during alkali activation of (Na-Mg) aluminosilicate glasses/ Harisankar Sreenivasan, Elijah Adesanya, He Niu, Priyadharshini Perumal, Anu M. Kantola, Ville-Veikko Telkki, Marko Huttula, Wei Cao, John L. Provis, Mirja Illikainen, Paivo Kinnunen. (2021) Cement and Concrete Research**

  DOI: 10.1016/j.cemconres.2021.106464

  There is some ambiguity regarding the fate of Mg during the alkali activation of Mg-rich precursors within the broader field of alkali activated materials (AAMs). The present work addresses this issue by studying the reaction products in AAMs synthesized from (Na-Mg) aluminosilicate glasses. Here, instead of magnesium

silicate hydrate (M-S-H) phase, Mg exclusively forms an amorphous magnesium silicate (AMS) phase. Compared to M-S-H, AMS is a more depolymerized phase, which has not previously been well documented. The formation of AMS seems to be driven by the high charge density of the Mg cation which effectively stabilizes the depolymerized silicate species. We also show that the lack of hydrotalcite-group phases is due to aluminum depletion by zeolite formation. This work highlights the need to consider the existence of the AMS phase in Mg-containing AAMs, especially in complex systems, where its identification may be difficult.

- **Mechanically activated mine tailings for use as supplementary cementitious materials/ Sivakumar Ramanathan, Priyadarshini Perumal, Mirja Illikainen, Prannoy Suraneni. (2021) RILEM Technical Letters**

  DOI: 10.21809/rilemtechlett.2021.143

  Two mine tailings are evaluated for their potential as supplementary cementitious materials. The mine tailings were milled using two different methods – ball milling for 30 minutes and disc milling for durations ranging from 1 to 15 minutes. The modified R^3 test was carried out on the mine tailings to quantify their reactivity. The reactivity of the disc milled tailings is greater than those of the ball milled tailings. Strong correlations are obtained between milling duration, median particle size, amorphous content, dissolved aluminum and silicon, and reactivity of the mine tailings. The milling energy results in an increase in the fineness and the amorphous content, which do not appreciably increase beyond a disc milling duration of 8 minutes. The reactivity increases significantly beyond a certain threshold fineness and amorphous content. Cementitious pastes were prepared at 30% supplementary cementitious materials replacement level at a water-to-cementitious materials ratio of 0.40. No negative effects of the mine tailings were observed at early ages in cement pastes based on isothermal calorimetry and thermogravimetric analysis, demonstrating the potential for these materials to be used as supplementary cementitious materials.

- **Influence of activator type on reaction kinetics, setting time, and compressive strength of alkali-activated mineral wools/ J. Yliniemi, B. Walkley, J. L. Provis, P. Kinnunen, M. Illikainen. (2021) Journal of Thermal Analysis and Calorimetry**

  DOI: 10.1007/s10973-020-09651-6

  Alkali activation is a promising utilisation route for mineral wool wastes, due to suitable chemical composition, high reactivity, and surface area. One key factor in the development of alkali-activated binders is the selection of the suitable alkali activator. Here, the effect of sodium hydroxide, sodium silicate, sodium aluminate, and sodium carbonate solution on the alkali-activation kinetics of two main types of mineral wools, stone wool and glass wool, is investigated. Setting time and

compressive strength development results are presented, which are explained and discussed in the context of isothermal calorimeter data obtained at temperature of 40 °C. Sodium hydroxide and sodium silicate solutions provided fast reaction with both mineral wools, evidenced by high heat release, high early strength, and fast setting. The reaction with sodium aluminate solution took several days to initiate, but it produced high compressive strength after 28 days of curing with both mineral wools. Glass wool reacted and hardened rapidly with sodium carbonate solution, but stone wool reacted slowly with sodium carbonate and exhibited a low extent of reaction, likely due to lower extent of reaction of stone wool under less alkaline conditions. These results show that mineral wool alkali activation kinetics and binder gel formation are controlled by the activator type and highlight the importance of choosing the most appropriate activator for each desired application.

- **One-part alkali-activated blast furnace slag for sustainable construction at subzero temperatures/ Ahmad Alzaza, Katja Ohenoja, Mirja Illikainen. (2021) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2020.122026

  The construction season is limited in northern countries due to the severe cold weather conditions and their detrimental impacts on concrete quality. Thus, there are excessive expenses required annually for insulation and energy-intensive heating systems for cold-weather concreting. This experimental study aimed to investigate the potential of using high-strength one-part alkali-activated blast furnace slag (AAS) in cold weather without the need for supplementary heating systems. Therefore, the impacts of different subzero curing temperatures on the hardened properties of one-part AAS mortar in comparison with cement mortar were assessed. After casting, mortars were immediately cured at a temperature of 23, −5, −10, and −20 °C, up to 56d. The results showed that the lower the curing temperature, the lower the UPV and compressive strength of cement and one-part AAS mortar; however when the curing period was fixed, one-part AAS mortar registered higher UPV and compressive strength than cement mortar at all curing temperatures. Owing to additional room temperature curing, the hardened properties of AAS mortar were significantly improved. The findings were further supported by microstructural and thermogravimetric analyses.

- **Characterization of mineral wool waste chemical composition, organic resin content and fiber dimensions: Aspects for valorization/ Juho Yliniemi, Rajeswari Ramaswamy, Tero Luukkonen, Ossi Laitinen, Álvaro Nunes de Sousa, Mika Huuhtanen, Mirja Illikainen. (2021) Waste Management**

  DOI: 10.1016/j.wasman.2021.06.022

Despite mineral wool waste is only a small fraction of total construction and demolition waste (CDW) by mass, it requires large transportation and landfilling capacities due to its low bulk density, and its utilization remains low compared to other CDW types. It is essential to understand the physical and chemical properties of this waste fraction in order to utilize it, e.g. as fiber reinforcement in composites or as supplementary cementitious material. Here, we provide a chemical and physical characterization of 15 glass wool and 12 stone wool samples of different ages collected from various locations across Europe. In addition, the chemical compositions of 61 glass and stone wool samples obtained from the literature are presented. Glass wool samples show little variation in their chemical composition, which resembles the composition of typical soda-lime silicate glass. Stone wool presents a composition similar to basaltic glass but with variability between samples in terms of calcium, magnesium, and iron content. Potentially toxic elements, such as Cr, Ba, and Ni, are present in mineral wools, but in low concentrations (<0.2%). Both wool types contain organic resin, which may decompose into smaller molecular fragments and ammonia upon heating or contact with alkaline solution. Mineral wool wastes have relatively similar length and width distributions, despite the age and type of the mineral wool. Overall, both mineral wool waste types have homogenous chemical and physical properties as compared to many other mineral wastes which makes their utilization as a secondary raw material promising.

- **Mineralogy and glass content of Fe-rich fayalite slag size fractions and their effect on alkali activation and leaching of heavy metals/ Adeolu Adediran, Juho Yliniemi, Mirja Illikainen. (2021) International Journal of Ceramic Engineering and Science**

  DOI: 10.1002/ces2.10107

  Fayalite slag (FS) is an Fe-rich nonferrous metallurgy (CaO-MgO-) FeOx-SiO_2 slag originating from nickel or copper manufacturing processes, which currently is disposed to landfills or used in low-value applications. This study investigates the mineralogy and glass content of certain sized fractions of FS and how it influences the reactivity, mechanical, and microstructural properties of the alkali-activated materials produced. Water-quenched granular FS was sieved into two size fractions: namely, a fine fraction (FF) with a particle size range of 0–0.5 mm and a coarse fraction (CF) with a particle size range of 1.5–2 mm. It was then milled to a similar median particle size of 10 μm to be used as a binder precursor. The reaction kinetics of each fraction was determined via thermal analysis microcalorimeter, and the microstructural evolution and chemical composition of the binder were studied using a scanning electron microscope coupled with an energy dispersive X-ray spectroscopy. The environmental leaching behavior of both fractions before and after alkali activation was assessed according to the EN 12457-2 standard. The results showed that both fractions consisted of fayalite, magnetite crystalline phases, and

$MgO-SiO_2-FeOx$ ($-CaO-Al_2O_3$) glass phase. However, FF had a higher glass content (63 wt.%) in comparison to CF (39 wt.%), and, consequently, FF was more reactive under alkali activation, as evidenced by faster reaction kinetics, faster strength development, and improved microstructural properties. Alkali-activated samples had differences in the chemical compositions of their binder gels at early stages, though later, their binders became increasingly homogenous and consisted of an Na-K-Fe-Si gel with Mg, Ca, and Al as minor constituents in both samples. Additionally, the leaching behavior of potentially toxic metals and substances from precursors and alkali-activated samples prepared was below the limits set for paved structures as specified by Finnish legislation.

- **Role of surfactants on the synthesis of impure kaolin-based alkali-activated, low-temperature porous ceramics/ Priyadharshini Perumal, Ali Hasnain, Tero Luukkonen, Paivo Kinnunen, Mirja I Ilikainen. (2021) Open Ceramics**

  DOI: 10.1016/j.oceram.2021.100097

  Porous ceramics were generated by direct foaming the alkali-activated unprocessed kaolin (impure kaolin, iK) with the addition of hydrogen peroxide (H_2O_2) and calcining at a low temperature of 400 °C. Hydrogen peroxide, a blowing agent, decomposes producing oxygen gas bubbles forming the porous structure in the fresh alkali-activated iK paste. In the present study, three different molarity of alkali activator (5, 10, or 15 M NaOH) were employed. The dosage of blowing agent (H_2O_2) was varied between 0 and 2% with a constant dosage of 0.5% (wt. of binder) of surfactant. The gas bubbles in fresh-state geopolymer slurry are unstable with a tendency to coalesce. In such cases, surfactants are introduced to improve the stability of the gas-liquid interface. Two different surfactants: non-ionic and cationic ones were used to study the properties of alkali-activated porous material. Fresh properties such as viscosity, yield stress, foaming rate, and fresh density were compared between reference iK samples without surfactants and those with surfactants. The mechanical and microstructural properties of alkali-activated (AA) low-temperature porous iK ceramics were determined after calcination. Pore structures were characterized with electron microscope to understand the interaction of different parameters during fresh/hardened state and their relevance with the changes in the mechanical properties. Surfactants, irrespective of the type, highly influenced the fresh properties of the AA-iK samples, which in turn reflected on the compressive strength of the porous ceramics.

- **High strength one-part alkali-activated slag blends designed by particle packing optimization/ Priyadharshini Perumal, Harisankar Sreenivasan, Tero Luukkonen, Anu M. Kantola, Ville-Veikko Telkki, Paivo Kinnunen, Mirja Illikainen. (2021) Construction and Building Materials**

DOI: 10.1016/j.conbuildmat.2021.124004

This paper focuses on the development of high-strength and eco-friendly one-part (i.e., dry-mix) alkali-activated mortar with ground granulated blast furnace slag as the main precursor. In addition to slag, phyllite dust and silica fume were used as co-binders in binary and ternary blends to improve mechanical properties. Particle packing optimization was employed for the mix proportioning to achieve a compact matrix skeleton. The results revealed that a 10% increase in mortar strength was gained after adjusting the particle packing and an additional 20% increment was observed after blending the slag with other mineral admixtures. Ternary blend with all three binders achieved a mortar compressive strength value of 145 MPa (at 28 d age), which is the highest strength reported in one-part alkali-activated materials. Additionally, ternary blends present potential economic benefits because of their ability to replace slag with lower-cost industrial side streams.

- **Development of Sustainable Alkali-Activated Mortars Using Fe-Rich Fayalitic Slag as the Sole Solid Precursor/ Adeolu Adediran, Juho Yliniemi, Mirja Illikainen. (2021) Frontiers in Built Environment**

DOI: 10.3389/fbuil.2021.653466

Vast amounts of water-cooled non-ferrous metallurgy slags are generated yearly, and significant amounts are unutilized or dumped in landfills. To address this issue, in this study, MgO-FeOx-SiO_2 fayalitic slag (FS) was used as the sole solid precursor (as an aggregate and binder) in alkali-activated mortars. The performance of the mortar samples was analyzed in terms of workability, density, compressive strength, and ultrasonic pulse velocity. The microstructural properties and binder composition of the samples were studied using a scanning electron microscope (SEM) coupled with energy dispersive X-ray spectroscopy (EDS). Experimental results revealed that mortar samples made with FS aggregates performed better, achieving a 28-day compressive strength of 21 MPa compared to mortars produced with standard sand aggregates, which gained compressive strengths of 9 MPa. Further optimization of the particle size distribution of FS aggregate-based mortar samples using particle packing technology improved the workability, densified the mortar and yielded a mechanical performance of up to 40 MPa. FS aggregates have better interfacial bonding with the binder gel compared to standard sand, and the FS aggregates participate in the hardening reactions, consequently affecting the final binder phase composition, which consists of a Na_2O-Fe_2O_3-SiO_2 gel with lower quantities of CaO, MgO, and Al_2O_3. Therefore, the alkali-activated mortars produced based on the optimization of fully recycled industrial residues can provide a pathway for the sole utilization of metallurgical by-products, which can have a wide range of structural applications.

- **Mechanical transformation of phyllite mineralogy toward its use as alkaliactivated binder precursor/ Elijah Adesanya, Katja Ohenoja, Juho Yliniemi, Mirja Illikainen. (2020) Minerals Engineering**

  DOI: 10.1016/j.mineng.2019.106093

  The mechanical activation of phyllite for use as an alkali-activated material was studied. Prolonged milling of phyllite resulted in reduced particle size and a structural reorganization of the material, leading to incremental increases in amorphous content, which further resulted in the improved reactivity of phyllite in an alkaline environment. Quantitative X-ray diffraction results showed that the phyllite consisted of quartz, muscovite, chamosite, albite, and X-ray amorphous phases. Among the crystalline phases, muscovite and chamosite underwent the most structural reorganization, leading to a more disordered structure due to prolonged and intensive milling. The structural reorganization was also established through Fourier-transform infrared spectroscopy. Dissolution tests in 6 M NaOH showed incremental increases in leached Al and Si elements with increased milling time. After geopolymerization of mechanically activated phyllite, calorimetric studies showed exothermic reactions, and a 28-day compressive strength of 25 MPa was achieved for paste samples cured at room temperature. This study ascertained the potential utilization of phyllite mineral waste in sustainable cement applications.

- **Mechanically Treated Fly Ash from Fluidized Bed Combustion of Peat, Wood, and Wastes in Concrete/ Katja Ohenoja, Valter Wigren, Jan Österbacka, Mirja Illikainen. (2020) Waste and Biomass Valorization**

  DOI: 10.1007/s12649-019-00615-y

  Fly ash generation in fluidized bed combustion (FBC) is a critical issue in many countries due to its disposal is becoming increasingly restricted and expensive. Because of this, there is a demand for applications in which these types of fly ashes could be utilized efficiently. One promising use for FBC fly ashes is as a cement replacement material in mortar and concrete. The current concrete regulations do not allow the use FBC fly ash as a supplementary cementitious material, but it can be expected to be included in the standards in the future. The properties of FBC fly ashes typically do not fulfill the values set in the standards as such. This study aimed to establish whether the properties of fly ashes from FBC of peat, wood, and wastes can be modified by mechanical classification and grinding so that they meet the requirements of the standards. The sulfate and chloride content, the sum of the main components (Si, Al, Fe), and the fineness of material were analyzed before and after the classification and grinding processes. In addition, the mortar specimens were prepared by using the processed fly ash as a cement replacement material. It was

found that air jet classification is an effective fractionating method for fly ashes that effectively removes sulfate and chloride into fine fraction. Classified and ground fly ashes are potential alternative cement replacement materials. It is possible to achieve 80% of the control sample's compressive strength and 90% of the control sample's flexural strength for mortars containing 20% of classified and ground FBC fly ashes.

- **Direct carbonation of peat-wood fly ash for carbon capture and utilization in construction application/ Katja Ohenoja, Jouni Rissanen, Paivo Kinnunen, Mirja Illikainen. (2020) Journal of CO2 Utilization**

  DOI: 10.1016/j.jcou.2020.101203

  Carbon dioxide (CO_2) emissions from industrial processes contribute largely to the greenhouse effect and climate change. One of these industries is the cement industry, which contributes around 8% of CO_2 emissions caused by mankind. Two promising and interesting ways to reduce CO_2 emission are the utilization of alternative cementitious materials and carbon capture and utilization through CO_2 mineralization. In this study, peat-wood fly ashes from fluidized bed combustion were used as a construction material for mineral carbonation. A self-hardening characteristic of this type of fly ash was utilized, and simultaneous carbonation and hydration reactions were studied. The study showed that fly ashes from the fluidized bed combustion of peat and wood could be used to capture and mineralize CO_2 during hydration reactions. At the same time, CO_2 could improve the strength of self-hardened fly ashes. One interesting future possibility is fly ash tile production at energy plants: fly ashes can be used to capture CO_2 from flue gases, thus improving the strength of produced tiles.

- **Surface Modification of Cured Inorganic Foams with Cationic Cellulose Nanocrystals and Their Use as Reactive Filter Media for Anionic Dye Removal/ Tuula Selkälä, Terhi Suopajärvi, Juho Antti Sirviö, Tero Luukkonen, Paivo Kinnunen, Ana Luiza Coelho Braga de Carvalho, Henrikki Liimatainen. (2020) ACS Applied Materials and Interfaces**

  DOI: 10.1021/acsami.0c05927

  In this work, a surface cationized inorganic–organic hybrid foam was produced from porous geopolymer (GP) and cellulose nanocrystals (CNCs). GPs were synthesized from alkali-activated metakaolin using H_2O_2 as a blowing agent and hexadecyltrimethylammonium bromide (CTAB) as a surfactant. These highly porous GPs were combined at pH 7.5 with cationic CNCs that had been synthesized from dissolving pulp through periodate oxidation followed by cationization in a deep eutectic solvent. The GP-CNC hybrid foams were employed as reactive filters in the

removal of the anionic dye, methyl orange (MO; 5–10 mg/L, pH 7). The effects of a mild acid wash and thermal treatments on the structure, properties, and adsorption capacity of the GPs with CNCs and MO were investigated. The CNCs aligned as films and filaments on the surfaces of the neutralized GPs and the addition of CNCs improved MO removal by up to 84% compared with the reference sample. In addition, CTAB was found to disrupt the attachment of CNCs on the pores and improve adsorption of MO in the GPs with and without CNCs.

- **Fiber reinforced alkali-activated stone wool composites fabricated by hot-pressing technique/ Hoang Nguyen, Alexandra Kaas, Paivo Kinnunen, Valter Carvelli, Carol Monticelli, Juho Yliniemi, Mirja Illikainen. (2020) Materials and Design**

  DOI: 10.1016/j.matdes.2019.108315

  Cementitious composite that has short molding time and high mechanical performance is favorable in pre-cast concrete industry. In this context, this study reports the use of hot-pressing technique to fabricate PVA fiber reinforced composites using alkali-activated stone wool (a waste from building insulation). Eight different mixtures were developed by varying the pressing time and temperature in comparison to the conventional oven-cured alkali-activated material. The mechanical performance of all compositions was evaluated under bending and compressive loadings. Life cycle assessment was used to investigate the greenhouse gas emission and embodied energy of the developed composites. The results reveal that PVA fibers greatly enhanced the mechanical performance of all reinforced mixtures with deflection hardening behavior and improvement in compressive strength. The hot-pressing technique lowered CO_2 emission and saved energy. Finally, a multi-criteria ranking method suggests hot-pressed PVA fiber reinforced cementitious composite, manufactured at 120 °C for 2 h, is the best composition attaining balance among energy spent, mechanical properties, and CO_2 footprint.

- **Improvement of mechanical strength of alkali-activated materials using micro low-alumina mine tailings/ Mahroo Falah, Katja Ohenoja, Robert Obenaus-Emler, Paivo Kinnunen, Mirja Illikainen. (2020) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2020.118659

  Low-alumina mine tailings (MTs) have shown the possibility of being a precursor in the production of alkali-activated materials (AAMs). The effects of the addition of sub-micron MTs (10 wt%) with the average size of 400 nm to improve the performance of AAMTs with alkali activator (10, 15, 20, and 30 wt% sodium silicate) were investigated by using X-ray diffractometry (XRD), Attenuated total reflection-Fourier-transform

infrared spectroscopy (ATR-FTIR), scanning electron microscopy (SEM), and nitrogen adsorption technique (BET). The mechanical properties of the materials were also analyzed. The results indicate that the addition of sub-micron MTs to AAMTs plays an important role in mineral compositions and enhances the mechanical strength performance in comparison to plain AAMTs, especially after just 7 days of aging. This result is attributed to the different microstructure between AAMTs and sub-micron MTs. BET results showed that the addition of sub-micron MTs reduces the total porosity of alkali-activated products and changes the pore structure. The pores of AAMTs were refined by the filling effects of sub-micron particles and the enhancement of the hydration process due to the nucleation effect of those sub-micron particles. This could be a significant reason for the increase in early age mechanical strength. This work introduces a novel approach to improve the performance of tailings-based alkali-activated materials using nano-sized precursors.

- **Nanostructural evolution of alkali-activated mineral wools/ J. Yliniemi, B. Walkley, J.L. Provis, P. Kinnunen, M. Illikainen. (2020) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2019.103472

  Mineral wools are the most widely used building insulation material worldwide. Annually, 2.5 million tonnes of mineral wool waste are generated in the EU alone, and this is a largely unutilised material that is landfilled or incinerated. However, mineral wool wastes are promising precursors for production of alkali-activated cementitious binders due to their favourable chemical and mineralogical composition and high surface area. Alkali-activation is therefore a valuable route for valorisation of large quantities of mineral wool waste. This study resolves the phase assemblage and nanostructure of reaction products formed upon alkali activation of stone wool and glass wool by sodium hydroxide and sodium silicate solutions with X-ray diffraction, electron microscopy and solid state nuclear magnetic resonance spectroscopy experiments probing ^{27}Al and ^{29}Si. The stone wool-based alkali-activated binder comprises an amorphous sodium- and aluminium-substituted calcium silicate hydrate (C-(N-)A-S-H) gel, an amorphous sodium aluminosilicate hydrate (N-A-S-H) gel and small amounts of the layered double hydroxide phase quintinite and zeolite F. The glass wool-based alkali-activated binder comprises an amorphous Ca- and Al-substituted sodium silicate (N-(C-)(A-)S–H) gel. Gel chemical composition and reaction kinetics of alkali-activated mineral wools are shown to be dependent on the activating solution chemistry, with reaction rate and extent promoted by inclusion of a source of soluble Si in the reaction mixture. This work provides the most advanced description of the chemistry and structure of alkali-activated mineral wools to date, yielding new insight that is essential in developing valorisation pathways for mineral wools by alkali

activation and providing significant impetus for development of sustainable construction materials.

- **Thermal stability of one-part metakaolin geopolymer composites containing high volume of spodumene tailings and glass wool/ Patrick N. Lemougna, Adeolu Adediran, Juho Yliniemi, Arnold Ismailov, Erkki Levanen, Pekka Tanskanen, Paivo Kinnunen, Juha Roning, Mirja Illikainen. (2020) Cement and Concrete Composites**

  DOI: 10.1016/j.cemconcomp.2020.103792

  This paper deals with the synthesis and thermal stability of one-part metakaolin geopolymer composites containing high volume of spodumene tailings (Quartz Feldspar Sand; QFS) and glass wool (GW). One of the objectives of the study was to prepare materials encompassing a maximum amount of waste streams with some potential thermal stability. Several compositions were prepared with sodium metasilicate anhydrous (Na_2SiO_3) wt.% of 0.5, 2.5, 5, 10 and 12,5. The one-part metakaolin geopolymer composites were cured at 60 °C for 24 h and the mechanical properties were assessed at 7 days and after post-heat treatment at 500, 750, 1000, 1100 or 1200 °C. X-ray diffraction, dilatometry, scanning electron microscopy and thermogravimetry analyses were used to study the stability of the prepared geopolymer composites until 1100–1200 °C. The results showed that more than 20 MPa compressive strength could be achieved with metakaolin geopolymer composites containing only 20 wt% of metakaolin. Metakaolin-GW geopolymer composites were stable up to 500 °C. Meanwhile, their counterparts containing QFS were stable up to 1100–1200 °C; samples prepared with higher dosage of sodium (Na_2SiO_3 > 5 wt%) retained more than 50% of their initial strength after thermal treatment at 1100 °C. Interestingly, for dosages of Na_2SiO_3 ≤ 5 wt%, more than 300% increase of strength was observed after thermal treatment at 1100–1200 °C. The use of QFS limited the thermal shrinkage at mild temperatures (<1000 °C), but favoured densification and strength development at 1100–1200 °C.

- **Immobilization of heavy metals, selenate, and sulfate from a hazardous industrial side stream by using calcium sulfoaluminatebelite cement/ Katri Piekkari, Katja Ohenoja, Visa Isteri, Pekka Tanskanen, Mirja Illikainen. (2020) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2020.120560

  Release of heavy metals from different industries and industrial waste is a major global threat for as well humans as ecosystems. In this study, immobilization of an industrial filter sludge (FS) with an extremely high content of several heavy metals

(24.6 wt% Pb, 21.7 wt% Hg, and 9.00 wt% Se) and sulfate via calcium sulfoaluminate-belite (CSAB) cement was tested. The ratios of 25%, 50% and 75% of CSAB addition were tested, and the target was to achieve immobilization of the hazardous components. The leaching of Pb, Hg, SeO_4, SO_4, Ni, Cd, Cu, and As was monitored, and the structure of the immobilized materials was examined via X-ray powder diffraction (XRD) and field emission scanning electron microscopy-energy dispersive spectroscopy (FESEM-EDS) analysis. It was observed that Hg, Cu, As, Cd, and Ni were immobilized completely and leaching of Pb was reduced by 69% from the theoretical release. On the other hand, the leaching of SeO_4 and SO_4 experienced major increase when CSAB was added. XRD indicated significant ettringite formation as the amount of added CSAB increased, and the formation of gypsum as the amount was decreased. FESEM-EDS indicated that the immobilization was largely based on encapsulation into the CSAB binder, but chemical immobilization into the ettringite binder was also observed. It was concluded that the increased release of SO_4 and SeO_4 might have resulted from an excess amount of sulfates (added gypsum) during hydration.

- **Microstructural Analysis and Strength Development of One-Part Alkali-Activated Slag/Ceramic Binders Under Different Curing Regimes/ Z. Abdollahnejad, T. Luukkonen, M. Mastali, C. Giosue, O. Favoni, M. L. Ruello, P. Kinnunen, M. Illikainen. (2020) Waste and Biomass Valorization**

  DOI: 10.1007/s12649-019-00626-9

  Alkali-activated binders have shown great potential in the reuse of industrial waste materials and have therefore received significant attention. The use of one-part or a “just-add-water” alkali-activated binder aims to avoid the use of alkali-activator solutions which have traditionally been utilized in two-part systems. By using a solid activator, the disadvantages posed by hazardous liquid activators (such as the difficulties of using them on-site) can be minimized. Ceramic materials represent a considerable fraction of construction and demolition wastes, and originate not only from the building process, but also as tiles from industry and rejected bricks. Besides using these waste materials as road sub-base or construction backfill materials, they can also be employed as supplementary cementitious materials or even as raw material for alkali-activated binders. This paper presents the strength development and microstructural results obtained from examining different compositions under various curing conditions (sealing, ambient, and submerged in water). Two different ceramic wastes (with and without firing) were used as a partial replacement (5–10% by mass) of ground granulated blast-furnace slag. Specimens were then cured under three different curing regimes, including: (1) plastic-sealed, (2) unsealed at ambient conditions with an average temperature of 23 °C and 35% RH, and (3) submerged in water until the test date. Mechanical testing (compressive and flexural strengths) and

microstructural analysis (SEM/EDX, XRD, MIP, heat of hydration, TGA, and DTA) were used to determine the effects of curing conditions. The results showed that ceramic waste content and type, as well as curing regimes, greatly affect the chemical reaction products, strength development, and structural stability.

- **Influence of sodium silicate powder silica modulus for mechanical and chemical properties of dry-mix alkali-activated slag mortar/ Tero Luukkonen, Harisankar Sreenivasan, Zahra Abdollahnejad, Juho Yliniem i, AnuKantola, Ville-Veikko Telkki, Paivo Kinnunen, Mirja Illikainen. (2020) Construction and Building Materials**

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  Sodium silicate powders with different SiO_2/Na_2O (silica modulus) were characterized by solubility rate, pH, and chemical structure (by ^{29}Si MAS-NMR) and compared in the preparation of one-part (or dry-mix) alkali-activated blast furnace slag mortar. The low SiO_2/Na_2O indicated the beneficial presence of less-polymerized silica (Q^1 and Q^2 Si environments) and thus faster dissolution. Consequently, using sodium silicates with SiO_2/Na_2O of 0.9, 2.1, and 3.4 resulted 28 d compressive strengths of 103, 80, and 2 MPa, respectively, with increasing setting time and decreasing heat release in isothermal calorimetry. Adjustment of activator SiO_2/Na_2O from 2.1 or 3.4 to 0.9 by adding NaOH powder resulted increased or decreased mechanical properties of mortar, respectively, depending on the initial silica modulus. These properties were not, however, similar to those obtained with sodium silicate having SiO_2/Na_2O of 0.9 originally. Depending on the case, the added NaOH can be consumed for dissolving sodium silicate activator, slag, or the forming (C,N)-(A)-S-H gel.

- **Sustainable batching water options for one-part alkali-activated slag mortar: Sea water and reverse osmosis reject water/ Tero Luukkonen, Juho Yliniemi, Paivo Kinnunen, Mirja Illikainen. (2020) PLoS ONE**

  DOI: 10.1371/journal.pone.0242462

  Concrete production is globally a major water consumer, and in general, drinking-quality water is mixed in the binder. In the present study, simulated sea water and reverse osmosis reject water were used as batching water for one-part (dry-mix) alkali-activated blast furnace slag mortar. Alkali-activated materials are low-CO2 alternative binders gaining world-wide acceptance in construction. However, their production requires approximately similar amount of water as regular Portland cement concrete. The results of the present study revealed that the use of saline water did not hinder strength development, increased setting time, and did not affect workability. The salts incorporated in the binder decreased the total porosity of

mortar, but they did not form separate phases detectable with X-ray diffraction or scanning electron microscopy. Leaching tests for monolithic materials revealed only minimal leaching. Furthermore, results for crushed mortars (by a standard two-stage leaching test) were within the limits of non-hazardous waste. Thus, the results indicated that high-salinity waters can be used safely in one-part alkali-activated slag to prepare high-strength mortars. Moreover, alkali-activation technology could be used as a novel stabilization/solidification method for reverse osmosis reject waters, which frequently pose disposal problems.

- **Utilization of Fly Ashes from Fluidized Bed Combustion: A Review/ Katja Ohenoja, Janne Pesonen, Juho Yliniemi, Mirja Illikainen. (2020) Sustainability (Switzerland)**

  DOI: 10.3390/su12072988

  Traditionally fly ash is thought to be glassy, spherical particle originating from pulverized coal combustion (PCC) at temperature up to 1700 °C. However, nowadays fluidized bed combustion (FBC) technology is spreading quickly around the world as it is an efficient and environmentally friendly method. FBC is also able to utilize mixtures of low-grade solid fuels (e.g., coal, lignite, biomass, and waste) that have fluctuating quality, composition, and moisture contents. However, this leads to a high variation in the produced fly ash quality, unlike PCC fly ash, and hence challenges when attempting to utilize this fly ash. In this study, the utilization of fluidized bed combustion fly ash (FBCFA) was reviewed using the Scopus database. The most promising utilization target for FBCFA from biomass combustion is as a fertilizer and soil amendment. In construction, the FBCFA from various fuels is utilized as cement replacement material, in non-cement binders, as lightweight aggregates and cast-concrete products. Other types of construction applications include mine backfilling material, soil stabilizer, and road construction material. There are also other promising applications for FBCFA utilization, such as catalysts support material and utilization in waste stabilization.

- **Production and properties of ferrite-rich CSAB cement from metallurgical industry residues/ Visa Isteri, Katja Ohenoja, Theodore Hanein, Hajime Kinoshita, Pekka Tanskanen, Mirja Illikainen, Timo Fabritius. (2020) Science of the Total Environment**

  DOI: 10.1016/j.scitotenv.2019.136208

  Blast furnace slag from the steel industry is commercially utilized as a cement replacement material without major processing requirements; however, there are many unutilized steel production slags which differ considerably from the blast furnace slag in chemical and physical properties. In this study, calcium

sulfoaluminate belite (CSAB) cement clinkers were produced using generally unutilized metallurgical industry residues: AOD (Argon Oxygen Decarburisation) slag from stainless steel production, Fe slag from zinc production, and fayalitic slag from nickel production. CSAB clinker with a target composition of ye'elimite-belite-ferrite was produced by firing raw materials at 1300 °C. The phase composition of the produced clinkers was identified using quantitative XRD analyses, and the chemical composition of the clinker phases produced was established using FESEM-EDS and mechanical properties were tested through compressive strength test. It is demonstrated that these metallurgical residues can be used successfully as alternative raw materials for the production of CSAB cement that can be used for special applications. In addition, it is shown that the available quantities of these side-streams are enough for significant replacement of virgin raw materials used in cement production.

- **Alternative alkali-activator from steel-making waste for one-part alkali-activated slag/ Elijah Adesanya, Katja Ohenoja, Andrea Di Maria, Paivo Kinnunen. (2020) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2020.123020

  n this study, the use of desulphurization dust (DeS-dust) generated as a waste material during steel-making process, as an alternative activator to commercial sodium hydroxide in ground granulated blast furnace slag (GGBFS) alkali activation is proposed. The main objective was to decrease the environmental footprint of alkali-activated materials through the reuse of industrial residues. Microsilica was added to increase the amount of soluble silica and enhance the properties of the investigated binders. The results indicate that binders from alternative activator performed better, achieving a 28 days maximum strength of 33 MPa compared to 25 MPa for the sodium hydroxide activated slag. Microsilica addition to the optimum mixes reduces the rate of efflorescence and increases the setting time. Also, microstructural studies using scanning electron microscopy (SEM), x-ray diffraction (XRD) and thermogravimetric analysis (TGA) show both samples having comparable gel formation and structure. Life cycle impact assessment shows significant savings that can be made using alternative activators over sodium hydroxide activated slag. Through the use of this waste material as alternative activator in alkali-activated binders, an environmentally friendly, and cleaner production of alkali-activated binders can be achieved having comparable or superior performance as the reference binder activated with commercial sodium hydroxide.

- **Removal of ammonium from wastewater with geopolymer sorbents fabricated via additive manufacturing/ Giorgia Franchin, Janne Pesonen, Tero Luukkonen, Chengying Bai, Paolo Scanferla, Renata Botti, Sara Carturan, Murilo Innocentini, Paolo Colombo. (2020) Materials and Design**

DOI: 10.1016/j.matdes.2020.109006

Geopolymers have been recently explored as sorbents for wastewater treatment, thanks to their mechanical and chemical stability and to their low-energy manufacturing process. One specific application could be the removal of ammonium (NH_4^+) through exchange with Na^+ ions. Additive manufacturing (AM) represents an especially interesting option for fabrication, as it allows to tailor the size, distribution, shape, and interconnectivity of pores, and therefore the access to charge-bearing sites. The present study provides a proof of concept for NH_4^+ removal from wastewater using porous geopolymer components fabricated via direct ink writing (DIW) AM approach. A metakaolin-based ink was employed for the fabrication of a log-pile structure with 45° rotation between layers, producing continuous yet tortuous macropores which are responsible for the high permeability of the sorbents. The ink consolidates in an amorphous, mesoporous network, with the mesopores acting as preferential sites for ion exchange. The printed sorbents were characterized for their physicochemical and mechanical properties and the NH_4^+ removal capacity in continuous-flow column experiments by using a model effluent. The lattices present high permeability and high cation exchange capacity and maintained a high amount of active ions after four cycles, allowing to reuse them multiple times.

- **Ag- or Cu-modified geopolymer filters for water treatment manufactured by 3D printing, direct foaming, or granulation/ Tero Luukkonen, Juho Yliniemi, Harisankar Sreenivasan, Katja Ohenoja, Mikko Finnilä, Giorgia Franchin, Paolo Colombo. (2020) Scientific Reports**

DOI: 10.1038/s41598-020-64228-5

In this work, we compared the main characteristics of highly porous geopolymer components for water treatment applications manufactured by 3D printing, direct foaming, or granulation. Furthermore, different approaches to impregnate the materials with Ag or Cu were evaluated to obtain filters with disinfecting or catalytic properties. The results revealed that all of the investigated manufacturing methods enabled the fabrication of components that possessed mesoporosity, suitable mechanical strength, and water permeability, even though their morphologies were completely different. Total porosity and compressive strength values were 28 vol% and 16 MPa for 3D-printed, 70–79 vol% and 1 MPa for direct-foamed, and 27 vol% and 10 MPa for granule samples. Both the filter preparation and the metal impregnation method affected the amount, oxidation state, and stability of Ag and Cu in the filters. However, it was possible to prepare filters with low metal leaching between a pH of 3–7, so that the released Ag and Cu concentrations were within drinking water standards.

- **Byproduct-based ettringite binder – A synergy between ladle slag and gypsum/ Hoang Nguyen, Elijah Adesanya, Katja Ohenoja, Lubica Kriskova, Yiannis Pontikes,Paivo Kinnunen, Mirja Illikainen. (2019) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2018.11.165

  Ladle slag (LS) is a byproduct from the steel industry that is usually reactive on its own and hydrates towards cementitious phases when mixed with water. However, these reaction products are often metastable, leading to micro-structural changes between 7 and 30 days after mixing. To address this issue, in this experimental investigation, a new binder was designed where LS was mixed with gypsum in order to deliver an ettringite-based binder (LSG). The experimental results revealed that the dominant crystalline phase of LSG was ettringite, which remained stable with no conversion at later stages. For better understanding of the ettringite-based binder, mortar characterization, mechanical properties, and durability of LSG were investigated. LSG showed good mechanical properties and excellent freeze-thaw resistance after 300 cycles, which is comparable to other calcium sulfoaluminate cements. Therefore, as a result, the byproduct-based ettringite binder synthesized herein could offer a solution to steelmaking byproducts with a low-CO_2 binder, which could be used in a wide range of applications in the construction industry.

- **Alkali-activated soapstone waste - Mechanical properties, durability, and economic prospects/ Tero Luukkonen, Zahra Abdollahnejad, Juho Yliniemi, Mohammad Mastali, Paivo Kinnunen, Mirja Illikainen. (2019) Sustainable Materials and Technologies**

  DOI: 10.1016/j.susmat.2019.e00118

  Soapstone is a soft, magnesium-rich mineral widely used in the production of carved objects and architectural elements, for instance. The processing of soapstone causes the formation of significant amounts of waste powder, which is largely landfilled at the moment. The aim of the present study is to evaluate the suitability of soapstone waste as the main binder for the alkali-activation process using sodium silicate and hydroxide solutions as activators. The results demonstrate that soapstone alone reacts to some extent (compressive strength of 13 MPa at 28 day age), but mechanical properties are improved significantly after replacing 20% of soapstone by metakaolin (compressive strength of 31 MPa at 28 d age). The obtained mechanical properties are closely similar to those of virgin soapstone. Durability properties of the developed alkali-activated binders were similar or better than typical Portland cement-based binders in terms of high temperature, acid, and freeze-thaw resistance, and sorptivity. The material costs alkali-activated soapstone mortar were

estimated as approximately 70 €/t. Thus, the results enable utilizing currently underexploited soapstone waste in a sustainable and economically interesting way.

- **Mine Tailings Geopolymers as a Waste Management Solution for A More Sustainable Habitat/ Helena Paiva, Juho Yliniemi, Mirja Illikainen, Fernando Rocha, Victor M. Ferreira, (2019) Sustainability (Switzerland)**

  DOI: 10.3390/su11040995

  The demand for low environmental impact of materials in our habitat is one of the current societal challenges. Along with other solutions of waste valorisation, alkali activation as geopolymers can be one possible solution of waste valorisation because they may allow, for instance, an alternative solution for cement-based materials in some applications and it is one contribution for circular economy. This work has focused on the development and processing of geopolymers that incorporates as a fine aggregate a high-sulfidic mining waste (mine tailing), a difficult waste to process. Rheology analysis was applied as an important step to understand not only the geopolymers behaviour but also its transition from the fresh to the hardened state. The effect of precursor binder type (metakaolin or blast furnace slag), of mine tailing content and also the effect of temperature and curing conditions of different formulations were studied in this solution. It was possible to conclude that although this particular mine tailing is not a geopolymer binder precursor, it may be incorporated as an alternative fine aggregate in construction products. Furthermore, rheology could be used to follow up the geopolymer alkali-activation process and even to setup proper curing conditions and components contents in order to optimize the final mechanical strength of this material as a waste management solution. The final properties of these geopolymers compositions were adequate and after 28 days of curing, these geopolymers exhibit significant chemical resistance under severe test conditions.

- **The effect of peat and wood fly ash on the porosity of mortar/ Jouni Rissanen, Chiara Giosué, Katja Ohenoja, Paivo Kinnunen, Mirco Marcell ini, Maria Letizia Ruello, Francesca Tittarelli, Mirja Illikainen. (2019) Construction and Building Materials**

  DOI: 10.1016/j.conbuildmat.2019.06.228

  Fluidized bed combustion fly ash (FBCFA), notably different from regular (coal) fly ash, is a promising industrial side stream to be used as a supplementary cementitious material (SCM). Peat and wood are important sources of biomass for energy production in Nordic countries and generate formidable amounts of un-used ash yearly. Two FBCFAs from the co-combustion of peat and wood, fly ash from coal combustion, and limestone filler were used to replace 10 wt%, 20 wt%, and 40 wt%

of cement in mortar specimens. The compressive strength, porosity, water absorption, water vapor permeability, and drying shrinkage of the mortars were measured and compared. It was found that in almost all properties FBCFAs outperformed un-reactive limestone filler. Compared to coal fly ash, FBCFAs produced mortars with comparable compressive strength although with higher porosity, water absorption, and water vapor permeability.

- **Solidification/stabilization of gold mine tailings using calcium sulfoaluminate-belite cement/ Jenni Kiventerä, Katri Piekkari, Visa Isteri, Katja Ohenoja, Pekka Tanskanen, Mirja Illikainen. (2019) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2019.118008

  In this study, calcium sulfoaluminate-belite cement (CSAB) was used to stabilize gold mine tailings, which are challenging materials to effectively immobilize due to high heavy metal and sulfate content. The hydration of CSAB cement yields ettringite and monosulfate with good capability for immobilizing sulfates and oxyanions in their crystal structure, in addition to physical encapsulation/solidification in a cementitious matrix. Different mix designs of CSAB cement and mine tailings were prepared, and the samples were cured at room temperature. Mechanical strength and heavy metal leaching were analyzed after 7 days, 28 days, and 90 days of curing, and the phase composition (XRD), thermogravimetric analysis (TGA), and microstructure (FESEM) were also studied. All harmful elements (cationic and oxyanion elements) were effectively immobilized during 7 days of curing, and the heavy metal immobilization remained constant after longer curing, according to an environmental leaching test. High mechanical strength results and good sulfate immobilization were obtained with mine tailing content up to 50 w-% of total binder material. With higher mine tailing content (75 w-% and 90 w-%), the mechanical strength and immobilization ability substantially decreased.

- **Geopolymers as active capping materials for in situ remediation of metal(loid)-contaminated lake sediments/ Johanna Kutunivaa, Jari Mäkinen, Tommi Kauppila, Anssi Karppinen, Seppo Hellsten, Tero Luukkonen, Ulla Lassib. (2019) Journal of Environmental Chemical Engineering**

  DOI: 10.1016/j.jece.2018.102852

  Metal(loid) contamination in sediments is a widespread environmental issue. Sediments act normally as metal(loid) sinks, but if chemical conditions (such as pH or redox potential) change, they can become sources of secondary pollution. Consequently, various strategies for both in and ex situ remediation of contaminated sediments have been developed. One promising method is active capping, which

involves the injection of adsorbents as a layer on the sediment surface or the mixing of adsorbents within the sediment. Adsorbents decrease the bioavailability of metal(loid)s. In the present work, the suitability of alkali-activated blast-furnace-slag, metakaolin geopolymer, and exfoliated vermiculite were evaluated for in situ stabilization of two metal(loid)-contaminated lake sediments through laboratory-scale experiments. The results indicated that adsorbent amendments had metal(loid)-specific performance: alkali-activated blast-furnace slag was suitable for Al, Cu, Fe, and Ni; metakaolin geopolymer for Cu, Cr (total), and Fe; and vermiculite for Al and Zn. None of the materials could stabilize Ba, Sr, or Ti. Furthermore, the amendments performed differently in two different lake sediments, implying that the effectiveness of the amendments needs to be confirmed on a case-by-case basis.

- **Suitability of commercial superplasticizers for one-part alkali-activated blast-furnace slag mortar/ Tero Luukkonen, Zahra Abdollahnejad, Katja Ohenoja, Paivo Kinnunen, Mirja Illikainen. (2019) Journal of Sustainable Cement-Based Materials**

  DOI: 10.1080/21650373.2019.1625827

  Alkali-activated materials are a low-CO_2 alternative for Portland cement in construction. However, one major issue in their use is the poor or varying functionality of the currently available commercial superplasticizers. Especially for one-part (‘just add water’) alkali-activated materials, the number of studies is limited. In this study, one-part alkali-activated mortar was prepared from blast furnace slag by using solid sodium hydroxide as an activator and microsilica as an additional silica source. Comparison of commonly used superplasticizer types revealed that lignosulfonate, melamine, and naphthalene-based superplasticizers are more efficient than the currently most used polyacrylate and polycarboxylate-superplasticizers. Lignosulfonate-based superplasticizer was overall best-performing: it improved significantly the workability (+41% spread, −51% yield stress, −27% viscosity), setting time (+70%), and compressive strength (+19%) at a 0.5 wt% dose. When the amount of water and superplasticizer were optimized, compressive strength of mortar could be doubled (from 19 to 40 MPa at 28 d).

- **Fly ash classification efficiency of electrostatic precipitators in fluidized bed combustion of peat, wood, and forest residues/ Katja Ohenoja, Mika Körkkö, Valter Wigren, Jan Österbacka, Mirja Illikainen. (2018) Journal of Environmental Management**

  DOI: 10.1016/j.jenvman.2017.10.047

  The increasing use of biomasses in the production of electricity and heat results in an increased amount of burning residue, fly ash which disposal is becoming more

and more restricted and expensive. Therefore, there is a great interest in utilizing fly ashes instead of just disposing of it. This study aimed to establish whether the utilization of fly ash from the fluidized bed combustion of peat, wood, and forest residues can be improved by electrostatic precipitator separation of sulfate, chloride, and some detrimental metals. Classification selectivity calculations of electrostatic precipitators for three different fuel mixtures from two different power plants were performed by using Nelson's and Karnis's selectivity indices. Results showed that all fly ashes behaved similarly in the electrostatic separation process SiO_2 resulted in coarse fractions with Nelson's selectivity of 0.2 or more, while sulfate, chloride, and the studied detrimental metals (arsenic, cadmium, and lead) enriched into fine fractions with varying selectivity from 0.2 to 0.65. Overall, the results of this study suggest that it is possible to improve the utilization potential of fly ashes from fluidized bed combustion in concrete, fertilizer, and earth construction applications by using electrostatic precipitators for the fractionating of fly ashes in addition to their initial function of collecting fly ash particles from flue gases. The separation of the finer fractions (ESP 2 and 3) from ESP 1 field fly ash is recommended.

- **Comparison of alkali and silica sources in one-part alkali-activated blast furnace slag mortar/ Tero Luukkonen, Zahra Abdollahnejad, Juho Yliniemi, Paivo Kinnunen, Mirja Illikainen. (2018) Journal of Cleaner Production**

  DOI: 10.1016/j.jclepro.2018.03.202

  Alkali-activated materials (AAMs) are one of the alternative low-CO_2 binders. One-part AAMs, (that is, mixing a solid precursor with a solid alkali activator and adding water) have recently attracted increasing interest. The purpose of this study is to examine if fast-dissolving solid synthetic sodium metasilicate could be replaced by a combination of sodium hydroxide and slow-dissolving silica derived from rice husk ash or microsilica in the preparation of one-part alkali-activated blast furnace slag mortar. The replacement would improve the carbon footprint and the cost efficiency of the binder. The results demonstrate that silica availability significantly affects compressive strength development as a function of time or mixture composition. The highest compressive strength (107 MPa, 28 d) was obtained with fast-dissolving silica. Furthermore, setting times could be adjusted based on the mix composition, and the durability of mortar remained good after 120 freeze–thaw cycles. The results highlight the overall effect of silica availability on the fresh and hardened properties of one-part AAMs.

- **Milling of peat-wood fly ash: effect on water demand of mortar and rheology of cement paste/ Rissanen Jouni, Ohenoja Katja, Kinnunen Paivo, Romagnoli Marcello, Illikainen Mirja. (2018) Construction and Building Materials**

DOI: 10.1016/j.conbuildmat.2018.05.014

The milling of fluidized bed combustion fly ashes is a promising method to improve ashes' properties as a cement replacement material. Two fly ashes from the co-combustion of peat and wood, as well as inert sand were milled at varying times. The physical properties of materials, water demand of mortar and rheology of cement paste were studied. At 25% cement replacement rate, the milling decreased the water demand of mortar by 10% and the yield stress of cement paste by 33%. It was found that milling disintegrated irregularly shaped particles, which were the main reason for high water demand of ashes, and tapped density could be used as a simple parameter to estimate the water demand for all studied materials.

- **Ladle slag cement – Characterization of hydration and conversion/ Elijah Adesanya, Harisankar Sreenivasan, Anu M. Kantola, Ville-Veikko Telkki, Katja Ohenoja, Paivo Kinnunen, Mirja Illikainen. (2018) Construction and Building Materials**

DOI: 10.1016/j.conbuildmat.2018.10.179

Ladle slag, a by-product of steelmaking process, has shown potential to be used as a cementitious material in construction. However, the stability of the hydration products has not been investigated, and has been found to depend on available water. This paper presents the investigation of ladle slag hydration at different water-to-binder ratios. Hydrates of ladle slag converts from metastable to a stable reaction product over a period of time, thus affecting the mechanical and microstructural properties of the hydrated slag. These hydration products were analyzed using TGA, XRD, ^{27}Al NMR, FTIR and SEM techniques. The water-to-binder ratio primarily contributes to the rate at which the conversion process occurs in the system which consequently has a direct effect on the strength derived over a period of time. Through analytical characterization of the microstructure, these hydrates and the conversion process were confirmed, revealing the initial hydrate product of ladle slag to be a metastable dicalcium aluminate octahydrate (C_2AH_8) which converts to a stable tricalcium aluminate hexahydrate (C_3AH_6) over a period of time.

- **One-part geopolymer cement from slag and pretreated paper sludge/ Elijah Adesanya, Katja Ohenoja, Tero Luukkonen, Paivo Kinnunen, Mirja Illikainen. (2018) Journal of Cleaner Production**

DOI: 10.1016/j.jclepro.2018.03.007

The aim of this study was the valorization of paper sludge waste from paper industry in designing one-part geopolymer cement using ground granulated blast furnace slag as main precursor. The effects of increasing the amount of paper sludge

pretreated with a constant amount of sodium hydroxide (2% of slag) on mechanical strength, heat evolution, setting time and durability were analyzed. The reaction products were characterized using X-ray diffraction and thermogravimetric analysis. The findings showed that paper sludge can successfully be used as a secondary source of calcium carbonate in the one-part ("just add water") geopolymer. The compressive strength of the cured geopolymer increased with increasing the amount of paper sludge, and the non-reacted sludge acted as a filler. The maximum strength (42 MPa, 28 d) was reached at 18 wt-% paper sludge addition. The main reaction products were calcium aluminate silicate hydrate and hydrotalcite-like cementitious gels. From the perspective of its blast-furnace slag content, strength properties, water absorption and setting time, the one-part geopolymer cement could be classified as a CEM IIIC and Type 32.5N class cement under the European standard EN-197.

- **Optimization of the metakaolin geopolymer preparation for maximized ammonium adsorption capacity/ Tero Luukkonen, Emma-Tuulia Tolonen, Hanna Runtti, Kimmo Kemppainen, Paavo Perämäki, Jaakko Rämö, and Ulla Lassi. (2017) Journal of Materials Science**

  DOI: 10.1007/s10853-017-1156-9

  Geopolymers are functional materials that can be used in various environmental applications such as adsorbents in pollutant removal from wastewaters. Metakaolin geopolymer (MK-GP) has been proven to be especially suitable for ammonium (NH_4^+) removal. In this research, the optimal reagent and raw material ratios in the preparation of MK-GP in terms of NH_4^+ adsorption capacity were investigated. The response surface methodology based on the face-centered central composite design was used to optimize the levels of three factors: the amounts of hydroxide, silicate, and metakaolin. In addition, the effect of Na or K as the charge-balancing cation was studied. Empirical models were fitted to the experimental data using multiple linear regression. The significance of the models was confirmed by means of analysis of variance. Optimal NH_4^+ removal efficiency was achieved when the amounts of hydroxide and silicate were maximized, the amount of metakaolin was minimized, and Na-based reagents were used. These trends are most likely a result of optimized conversion of metakaolin into MK-GP.

- **Ligand-assisted dissolution and surface studies of phlogopite : aspects for utilization/ Akbarzadeh Khoei, Mahtab 2026**

  https://urn.fi/URN:NBN:fi:oulu-202511056593

  A wide range of silicate mineral wastes are generated globally, yet their practical utilization is often hindered by their inherently low dissolution rates. This thesis explores various strategies to enhance the dissolution of phlogopite—a robustly

structured mica-group mineral and a mining byproduct. The research focuses on identifying whether and how specific treatments improve the dissolution behavior of phlogopite. Insights gained from this study not only deepen our understanding of phlogopite reactivity but also offer potential approaches to boost the dissolution and utilization prospects of other silicate-based waste materials. Additionally, this thesis presents an investigation of the potential of phlogopite as a sustainable raw material, focusing on its role in potassium recovery for downstream uses such as fertilizer applications and its suitability as a precursor for alkali-activated materials, without addressing fertilizer formulation.

In mechanical treatment, milling was used to disrupt the crystalline structure, producing nanocrystalline domains within an amorphous matrix and exposing interlayer potassium. The leaching behavior of the milled phlogopite was studied under different pH conditions and in the presence of organic ligands such as ethylenediamine, citrate, and oxalate. Ultrasound-assisted leaching further improved the dissolution of key elements (such as K and Mg), with surface and structural analyses confirming morphological changes and interactions between ligand and the surface. To further increase elemental extraction, especially for K recovery, under high solid-to-liquid ratios, phlogopite was co-milled with gypsum and leached using citric acid. Co-milling phlogopite with gypsum introduced Ca^{2+} ions that disrupt the T–O–T silicate bridges, weakening the structure. In addition, the presence of citric acid and sulfate ions enhanced K dissolution, while altering the crystalline phase assemblage of the residues as well.

The silicate-rich residue obtained after leaching in citric acid solution using sonication was dissolved in sodium hydroxide to produce an alkali activator solution. This solution, containing SiO_2, K_2O, and Na_2O, was used to activate blast furnace slag. The resulting binders exhibited improved mechanical strength and microstructural density, with hydration products such as C-(N)-A-S-H, layered double hydroxides, and calcite confirmed through SEM, XRD, and thermogravimetric analysis. These findings demonstrate that phlogopite, when properly treated, can be effectively valorized as both a source of K and a precursor for alkali activators, offering a promising pathway for the circular use of mining side streams in sustainable construction materials.

Laaja kirjo silikaattipohjaisia mineraalijätteitä muodostuu eri puolilla maapalloa, joiden hyödyntämistä rajoittaa usein niiden luontaisesti alhainen liukenemisnopeus. Tässä väitöskirjassa tutkitaan erilaisia menetelmiä flogopiitin liukenemisen tehostamiseksi; flogopiitti muodostuu kaivostoiminnan sivuvirtana ja sillä on luja mineraalirakenne. Tutkimuksen tavoitteena on selvittää, missä määrin ja millä mekanismeilla erilaiset käsittelyt parantavat flogopiitin liukenemiskäyttäytymistä. Saatu tieto syventää ymmärrystä flogopiitin reaktiivisuudesta ja tarjoaa samalla uusia lähestymistapoja muiden silikaattipohjaisten jätteiden liukenemisen ja

hyödyntämispotentiaalin parantamiseen. Lisäksi väitöskirjassa arvioidaan flogopiitin potentiaalia ympäristöystävällisenä raaka-aineena esimerkiksi alkaliaktivoitujen materiaalien sovelluksissa.

Mekaanisessa käsittelyssä flogopiittia jauhettiin, jolloin sen kiderakenne hajosi ja muodostui amorfinen matriisi, jossa oli nanokiteisiä alueita. Jauhetun flogopiitin liukenemista tutkittiin eri pH olosuhteissa ja orgaanisten ligandien, kuten etyleenidiamiinin, sitraatin ja oksalaatin, läsnä ollessa. Ultraäänellä tehostettu liuotus paransi kaliumin ja magnesiumin liukenemista, ja rakenneanalyysit osoittivat morfologisia muutoksia ja ligandien vuorovaikutuksia flogopiitin pinnan kanssa. Kaliumin talteenoton tehostamiseksi flogopiittia jauhettiin suurilla kiinteä/nestesuhteilla yhdessä kipsin kanssa ja liuotettiin sitruunahapolla. Kipsin mukana tulleet kalsiumionit hajottivat silikaattiverkon T–O–T-siltoja, heikentäen rakennetta. Sitruunahapon ja sulfaatti-ionien läsnäolo lisäsi kaliumin liukenemista ja muutti jäännöksen kiteistä faasikoostumusta. Sitruunahappoliuoksessa ultraäänellä liuotettu silikaattipitoinen jäännös liuotettiin natriumhydroksidiin alkaliaktivaattorin valmistamiseksi. Tämä liuos, joka sisälsi SiO2:ta, K2O:ta ja Na2O:ta, käytettiin masuunikuonan aktivoimiseen. Tuloksena saadut sideaineet osoittivat laasteilla olevan parempi mekaaninen lujuus ja tiiviimpi mikrorakenne, ja niiden hydrataatiotuotteina havaittiin muun muassa C-(N)-A-S-H-geeliä, kerrostuneita kaksoiskerroshydroksideja ja kalsiittia SEM-, XRD- ja TGA-analyyseillä. Tulokset osoittavat, että flogopiittia voidaan sopivalla tavalla käsiteltynä hyödyntää tehokkaasti sekä kaliumin lähteenä että alkaliaktivaattorin raaka-aineena, tarjoten lupaavan reitin kaivossivuvirtojen kiertotaloudelliseen hyödyntämiseen ympäristöllisesti kestävissä rakennusmateriaaleissa.

- **Ammonium removal and recovery from wastewater with porous geopolymers/ Yu, Yangmei 2025**

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  Porous geopolymer granules are emerging as a promising material for high-value applications such as adsorption and ammonium (NH_4^+) recovery from wastewater. This thesis presents a comprehensive investigation into the fabrication, characterization, and application of porous metakaolin-based geopolymer granules produced via direct foaming, one-part alkali activation, and high-shear granulation. Porosity was introduced using either hydrogen peroxide (H_2O_2) or municipal solid waste incineration fly ash containing metallic aluminum (Al0) as blowing agents. Increased porosity, particularly in the micro- and nanoscale range, significantly enhanced the specific surface area and NH_4^+ adsorption capacity—up to 126% higher compared to nonporous granules, with optimal performance observed using 10% H_2O_2 solution. The granules demonstrated sufficient mechanical strength (≥2 MPa) and were evaluated for environmental safety and ion-exchange behavior. While

fly ash improved porosity, it introduced leaching concerns for elements like antimony and vanadium, limiting its optimal content to 0.3 wt.% Al0. Adsorption-desorption studies showed that porous geopolymer granules achieved an average NH_4^+ uptake capacity of up to 9.0 mg/g, and NH_4^+ recovery of 51–98% over the 30 adsorption and desorption cycles using KNO_3 as a regenerant, though performance declined after 20 cycles. Application in municipal wastewater highlighted the need for pretreatment to mitigate pore blocking and surface fouling. Overall, these findings establish porous geopolymer granules as a feasible, regenerable, and effective material for NH_4^+ recovery, contributing to circular nitrogen economy and sustainable wastewater treatment strategies.

Huokoiset geopolymeerirakeet ovat nousemassa lupaavaksi materiaaliksi korkean lisäarvon sovelluksiin, kuten adsorptioon ja ammoniumin (NH_4^+) talteenottoon jätevedestä. Tämä väitöskirja esittelee kattavan tutkimuksen metakaoliinipohjaisten huokoisten geopolymeerirakeiden valmistuksesta, karakterisoinnista ja käytöstä hyödyntäen vaahdotusta, alkaliaktivointia sekä granulointia. Huokoisuutta lisättiin käyttämällä vaahdotusaineina joko vetyperoksidia (H_2O_2) tai yhdyskuntajätteenpolton lentotuhkaa, joka sisälsi metallista alumiinia (Al0). Huokoisuuden lisääntyminen, erityisesti mikro- ja nanokokoluokissa, paransi merkittävästi rakeiden ominaispinta-alaa ja NH_4^+-adsorptiokapasiteettia – jopa 126 % verrattuna ei-huokoisiin rakeisiin. Paras suorituskyky saavutettiin 10 % H_2O_2-liuoksella. Rakeet osoittivat riittävää mekaanista lujuutta (≥2 MPa), ja niitä arvioitiin myös ioninvaihtokyvyn osalta. Vaikka lentotuhka lisäsi huokoisuutta, se aiheutti haitallisten aineiden, kuten antimonin ja vanadiinin, liukenemista, minkä vuoksi optimaalinen tuhkapitoisuus rajoitettiin 0.3 paino-% Al0:aan. Adsorptio-desorptiotutkimukset osoittivat, että huokoiset geopolymeerirakeet saavuttivat keskimääräisen NH_4^+-ottokapasiteetin jopa 9.0 mg/g ja NH_4^+-saannon 51–98 % 30 adsorptio- ja desorptiosyklin aikana, kun KNO3 20:a regeneroivana aineena käytettiin, vaikka suorituskyky heikkeni syklin jälkeen. Pitkän aikavälin käytössä suorituskyky kuitenkin heikkeni. Kunnallisen jäteveden käsittelyssä havaittiin huokosten tukkeutumista ja pintaan kertyvää kiintoainesta, mikä korostaa esikäsittelyn merkitystä. Yhteenvetona voidaan todeta, että huokoiset geopolymeerirakeet ovat käyttökelpoinen, uudelleenkäytettävä ja tehokas materiaali NH_4^+:n talteenottoon, edistäen typen kiertotaloutta ja kestävää jäteveden käsittelyä.

- **Magnesium-based glasses prepared by sol-gel processing for use as supplementary cementitious materials/ Jiang, Chuqing 2025**

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  For decades, supplementary cementitious materials (SCMs) have been utilized as clinker substitutes as one of the strategies to mitigate the CO2 emissions associated with Portland cement production. However, traditional SCMs (e.g., coal

fly ash, silica fume, and blast furnace slag) are being phased out, as they are insufficient to enable high volume clinker substitution. Therefore, alternative SCMs are actively being sought to meet market demand. Synthetic glasses may be a potential source of SCMs due to their pozzolanic activity and tunable properties. The chemical composition of glasses determines their pozzolanic activity, with Ca-based glasses being predominantly studied owing to their high reactivity. However, this leads to the same inherent CO2 emissions as for cement, originating from the production of CaO from CaCO3.

This thesis investigates Mg-based silicate glasses synthesized via the sol-gel method, tuning their composition for higher pozzolanic activity. The feasibility of using Mg-based silicate glasses as SCMs was studied through three main pathways:

(1) Development of a binary Mg-Si sol-gel glass system: The impact of varying Mg concentrations on the glass reactivity was assessed (Publication Ⅰ).

(2) Introduction of Fe into the Mg-Si system: Varying concentrations of Fe3+/ Fe2+ were incorporated into Mg-Si glasses, investigating changes in reactivity (Publications Ⅱ, Ⅲ).

(3) Assessment of cementitious performance: The pozzolanic activity of Mg-based glasses was evaluated, and their impact on the properties and performance of cementitious systems was studied (Publication Ⅳ).

The research revealed the high elemental solubility of the synthetic glasses, indicating their high reactivity, and demonstrated pozzolanic activity exceeding that of conventional SCMs such as fly ash slag. These findings provide a preliminary assessment of the potential for using Mg silicate glasses as novel SCMs with the aim of reducing CO2 emissions.

Jo vuosikymmenten ajan sementin seosaineita (SCM) on käytetty klinkkerin korvikkeina tavoitteena vähentää portlandsementin tuotannossa syntyviä CO2-päästöjä. Perinteisten SCM-materiaalien, kuten lentotuhkan, silikajauheen ja masuunikuonan, saatavuus ei kuitenkaan riitä mahdollistamaan korkeaa klinkkerin korvausastetta. Siksi on tarpeen kehittää uusia SCM-materiaaleja markkinoiden tarpeiden täyttämiseksi. Synteettiset lasit voivat olla potentiaalinen vaihtoehto niiden potsolaanisen aktiivisuuden ja säädettävien ominaisuuksien ansiosta. Lasien kemiallinen koostumus määrittää niiden potsolaanisen aktiivisuuden, ja enimmäkseen on tutkittu Ca-pohjaisia laseja niiden korkean reaktiivisuuden vuoksi. Tämä johtaa kuitenkin samoihin luontaisiin CO2-päästöihin kuin sementin tuotannossa, koska CaO:ta tuotetaan CaCO3:sta.

Tämä väitöskirja tutkii Mg-pohjaisia silikaattilaseja, jotka tuotetaan sol-gel-menetelmällä, jossa lasien koostumusta säädetään korkeamman potsolaanisen aktiivisuuden saavuttamiseksi. Mg-pohjaisten silikaattilasien käyttökelpoisuutta SCM-materiaaleina tutkittiin kolmen pääasiallisen lähestymistavan kautta:

(1) Binaarisen Mg-Si sol-gel-lasin kehitys: Eri Mg-pitoisuuksien vaikutuksia lasin reaktiivisuuteen arvioitiin (julkaisu I).

(2) Fe:n lisääminen Mg-Si-järjestelmään: Mg-Si-laseihin lisättiin eri pitoisuuksia Fe3+/Fe2+:aa, ja niiden vaikutusta reaktiivisuuteen tutkittiin (julkaisut II, III).

(3) Sementtimäisen suorituskyvyn arviointi: Mg-pohjaisten lasien potsolaanista aktiivisuutta arvioitiin, ja niiden vaikutusta seostettujen sementtien ominaisuuksiin ja suorituskykyyn tutkittiin (julkaisu IV).

Tutkimus paljastaa synteettisten lasien korkean alkuaineliukoisuuden, mikä viittaa niiden korkeaan reaktiivisuuteen, sekä osoittaa, että niiden potsolaaninen aktiivisuus ylittää perinteiset SCM:t, kuten lentotuhkan ja kuonan. Nämä havainnot tarjoavat alustavan arvion Mg-silikaattilasien potentiaalista uusina SCM-materiaaleina, joiden tavoitteena on CO2-päästöjen vähentäminen.

- **Insights into the role of additives on the hydration and carbonation of magnesium oxide and stability of the carbonates/ Kamala Ilango, Nirrupama 2025**

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  Magnesium carbonate-based minerals can capture and store CO2 as stable mineral carbonates and be utilized to produce construction materials with a low or negative carbon footprint compared to conventional Portland cement. However, several challenges exist in such binders that need to be addressed to enable their use in practical applications. This thesis aims to address two main issues: i) the reactivity of MgO and ii) the phase stability of the carbonation products.

  The effect of organic additives (acetate, formate and citrate) on the reaction kinetics and products formed during the hydration of MgO and on subsequent carbonation were studied. According to the findings, the organic additives accelerate or retard the hydration kinetics while also modifying the crystallinity and in some cases the crystal structure of the precipitated brucite. The solubility products of the organo-modified brucite were estimated and found to be slightly lower than that of pure brucite. Furthermore, on reaction with CO2, organic-modified brucite forms different carbonate phases compared to analytical brucite implying the role of additives in

steering the carbon mineralization pathways.

Nesquehonite is the most readily formed hydrated magnesium carbonate (HMC) at near ambient conditions and has the highest C:Mg ratio compared to most other HMCs. In the second part of the thesis, two different approaches to stabilize the phase were investigated. First, the possibility of formation of solid solution by doping the system with a cation (Zn2+) of similar ionic radius to that of Mg2+ was explored. In the second approach, the effect of solution equilibrium between HCO3- and CO32- ions with the addition of HCl, Na2CO3, and pH 7 buffer solutions in stabilizing nesquehonite was investigated. It was found that doping with Zn2+ stabilized dypingite instead of nesquehonite. In the second approach, although the equilibrium of carbonate in an aqueous environment did not stabilize nesquehonite, the phosphate from the buffer solution formed an insoluble magnesium phosphate hydrate which prevented nesquehonite from further conversion, thereby stabilizing the phase.

Magnesiumkarbonaattipohjaiset mineraalit voivat sitoa ja varastoida hiilidioksidia pysyvinä karbonaattimineraaleina, ja niitä voidaan käyttää tuottamaan rakennusmateriaaleja, joilla on alhainen tai negatiivinen hiilijalanjälki. Tällaisissa sideaineissa on haasteita, jotka on ratkaistava, jotta materiaaleja voidaan hyödyntää käytännön sovelluksissa. Tämän työn tavoitteena on käsitellä kahta pääkysymystä, i) MgO:n reaktiivisuutta ii) karbonaatiotuotteiden faasistabiilisuutta.

Tutkimuksen kohteena oli orgaanisten lisäaineiden (asetaatin, formiaatin ja sitraatin) vaikutus reaktiokinetiikkaan ja MgO:n hydraation ja karbonaation aikana muodostuviin tuotteisiin. Orgaaniset lisäaineet kiihdyttävät tai hidastavat hydraatiokinetiikkaa samalla, kun ne muuttavat saostuneen brusiitin kiteisyyttä ja joissakin tapauksissa sen kiderakennetta. Arvioitiin organomodifioitujen brusiittien liukoisuustuloja, ja niiden todettiin olevan alhaisemmat kuin puhtaan brusiitin. Lisäksi havaittiin, että orgaanisesti modifioitu brusiitti muodostaa hiilidioksidin kanssa reagoidessaan erilaisia karbonaattifaaseja verrattuna analyyttiseen brusiittiin, mikä viittaa lisäaineiden vaikutukseen hiilen mineralisaatioreittien ohjautumisessa.

Nesquehoniitti on helpoimmin vallitsevissa olosuhteissa muodostuva hydratoitu magnesiumkarbonaatti (HMC), ja sillä on korkein C:Mg-suhde verrattuna useimpiin muihin HMC-yhdisteisiin. Tämän väitöskirjan toisessa osassa tutkittiin kahta lähestymistapaa faasin stabiloimiseksi. Tarkasteltiin kiinteän liuoksen muodostumisen mahdollisuutta seostamalla järjestelmää kationilla (Zn^{2+}), jonka ionisäde on samanlainen kuin Mg^{2+}:lla. Toisessa lähestymistavassa tutkittiin liuostasapainon vaikutusta HCO_3^- ja CO_3^{2-} ionien välillä, jossa lisättiin HCl-, Na_2CO_3- ja pH 7-puskuriliuoksia nesquehoniitin stabiloimiseksi. Havaittiin, että Zn^{2+}

stabiloi dypingiitin nesquehoniitin sijaan. Toisessa lähestymistavassa, vaikka karbonaatin tasapaino vesipitoisessa ympäristössä ei stabiloinut nesquehoniittia, puskuriliuoksen fosfaatti muodosti liukenemattoman magnesiumfosfaattihydraatin, joka esti nesquehoniitin jatkomuuntumisen ja siten stabiloi faasin.

- **Dissolution-precipitation reactions of amorphous multi-oxide silicates: application of ligands in low-CO2 cementitious binders/ Ramaswamy, Rajeswari 2025**

  https://urn.fi/URN:NBN:fi:oulu-202502071528

  Utilization of inorganic waste in the production of alkali-activated materials (AAMs) has shown potential to reduce CO2 emissions and energy usage compared to the production of traditional cement and concrete. Two such wastes are mineral wool and ground granulated blast furnace slag which are composed of amorphous multi-oxide silicates. Insights into the hydration mechanisms of AAMs are still being explored, which limits the utilization of these wastes. This thesis aims to develop an understanding of the factors controlling the dissolution-precipitation reactions of these wastes in alkaline conditions and to modify their reaction properties by using ligands as a new type of chemical admixture to produce low-CO2 cementitious binders.

  Various analytical and microscopic techniques were employed to understand the dissolution and precipitation chemistry on the solid-solution interface. The results showed that mineral wool has a homogenous median chemical composition, fiber length, and width for their respective types. The dissolution-precipitation reactions of mineral wool are affected by the pH, liquid-to-solid ratio, and chemical composition. Stone wool dissolved better than glass wool in alkaline conditions and the formation of precipitates such as Mg-Fe-Al-Ti layered double hydroxides and Ca-Na-Al-Si hydrate gel for both wools at pH 14 and the formation of phyllosilicates (Mg-Si-Al-Fe) for stone wool at pH 11 was observed. These results confirm the potential of mineral wool as a secondary raw material for AAMs.

  Five types of ligands were investigated as accelerators for Na2CO3-activated slag binder. The most promising was 2,3-dihydroxynaphthalene (DHNP), which showed an acceleration of the reaction kinetics of Na2CO3-activated slag, producing a strength of 40 MPa at 2 d compared to the strength of the reference sample without ligand of 2 MPa. Ligand properties like functional group and concentration affected the reaction kinetics and mechanism compared to the reference. Dissolution studies showed that DHNP increases the extent of dissolution significantly compared to the reference due to complexation reactions with Si and Ti, which accelerated the precipitation kinetics and increased the quantity of carbonate phases. Additionally, DHNP affected the morphology of the phyllosilicate phases. These results confirm

the potential of ligands as new chemical admixtures to produce sustainable engineered cementitious binders.

Teollisuuden epäorgaanisten jätteiden hyödyntäminen alkaliaktivoitujen materiaalien tuotannossa voi alentaa CO2-päästöjä ja energiankulutusta verrattuna perinteisen sementin ja betonin tuotantoon. Kaksi tällaista jätettä ovat mineraalivilla ja jauhettu masuunikuona, jotka koostuvat amorfisista multioksidisilikaateista. Alkaliaktivoitujen materiaalien hydrataatiomekanismeja tutkitaan edelleen, mikä rajoittaa näiden jätteiden hyödyntämistä. Tämän väitöskirjan tavoitteena on parantaa ymmärrystä näiden jätteiden liukenemis-saostumisreaktioista emäksisissä olosuhteissa säätelevistä tekijöistä ja muokata niiden reaktio-ominaisuuksia käyttämällä ligandeja uudenlaisena kemiallisena lisäaineena vähähiilisten sementtimäisten sideaineiden valmistuksessa.

Työssä käytettiin useita analyyttisiä ja mikroskooppisia tekniikoita liukenemis- ja saostumiskemian tutkimiseen kiinteä-liuosrajapinnalla. Tulokset osoittivat, että mineraalivilloilla on homogeeninen kemiallinen koostumus, kuidun pituus ja että mineraalivillan liukenemis-saostumisreaktioihin vaikuttavat pH, neste-kiintoaine-suhde ja kemiallinen koostumus. Kivivilla liukenee paremmin kuin lasivilla emäksisissä olosuhteissa ja niissä muodostuu useita erilaisia saostumia, kuten kerroksellisia Mg-Fe-Al-Ti-pitoisia hydroksideja, Ca-Na-Al-Si-pitoisia hydraattigeelejä ja Mg-Si-Al-Fe-pitoisia phyllosilikaatteja, riippuen villatyypistä ja pH:sta. Nämä tulokset vahvistavat mineraalivillojen potentiaalin alkaliaktivoitujen materiaalien vaihtoehtoisena raaka-aineena.

Viittä erityyppistä ligandia tutkittiin Na2CO3-aktivoidun masuunikuona-pohjaisen sideaineen kiihdyttimenä. Lupaavin oli 2,3-dihydroksinaftaleeni, joka nopeutti Na2CO3-aktivoidun masuunikuonan reaktiokinetiikkaa ja tuotti 40 MPa:n lujuuden kahdessa vuorokaudessa verrattuna vertailunäytteen 2 MPa lujuuteen ilman ligandia. Ligandin ominaisuudet, kuten funktionaaliset ryhmät ja pitoisuus, vaikuttivat reaktiokinetiikkaan ja reaktiomekanismiin. Liukenemistutkimukset osoittivat, että 2,3-dihydroksinaftaleeni merkittävästi lisää liukenemisastetta verrattuna referenssinäytteeseen johtuen kompleksointireaktioista Si:n ja Ti:n kanssa, mikä nopeutti saostumiskinetiikkaa ja lisäsi karbonaattifaasien määrää. Lisäksi DHNP vaikutti phyllosilikaattifaasien morfologiaan. Nämä tulokset vahvistavat ligandien potentiaalin uusina kemiallisina lisäaineina vähähiilisten sementtimäisten sideaineiden valmistuksessa.

- **Utilization of pulp mill side streams as a part of cementitious binders/ Rasmus, Juho 2025**

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Different industries produce vast amounts of residue that can be used as raw materials in cementitious systems. In the context of this thesis, the most important systems include alkali-activated materials (AAMs) and supplementary cementitious materials (SCMs). This thesis concentrates on two pulp mill residues: recovery boiler fly ash (RBA) and green liquor dregs (GLD). The aim was to find out whether these residues would work as alternative alkali activators, since the challenge faced by AAMs is the high environmental footprint of commercial activators. Two RBAs were used as-received, while three batches of daily GLD samples were first combined to produce three GLDs, which were then thermally treated at moderately low temperatures (105 °C, 300 °C, 525 °C, or 650 °C).

Results proved that both RBAs and thermally treated GLDs activated blast furnace slag-based precursors. RBA, which is rich in sodium sulfate, showed similar or superior activating properties to commercial sodium sulfate, and common hydration products were formed during hydration. According to the results, a suitable dosage of RBA was 1–3 wt.% (Na_2O eq.). In the GLD experiments, it was found that thermal pretreatment (Tmax 525 °C) modified the properties of GLD by removing most of the remaining organic carbon and increasing the amount of soluble calcium, which led to an increased pH. It was also found that, in addition to $CaCO_3$, complex magnesium-rich phases including layered double hydroxide group phases (LDHs) occurred in GLDs.

The activating effect of thermally treated GLDs was enhanced by a higher treatment temperature. However, at 28 days, samples activated with GLD treated at 300 °C gained the highest strength. In the SCM experiments, 25% of cement was substituted with thermally treated GLDs and it was found that the addition of GLD decreased the 90-day strength by more than 15%. In both systems, AAM and SCM, the addition of GLD increased the viscosity and reduced the workability; however, both of these impacts were decreased by a higher pretreatment temperature. One interesting finding was that LDHs were also found in hydrated samples including GLDs treated at 525 °C or 650 °C, indicating the possible reconstruction of these phases after thermal treatment. To summarize, GLDs, earlier seen as non-reactive material, exhibited an activating effect on blast furnace slag.

Eri teollisuudenalat tuottavat suuria määriä sellaisia sivuvirtoja, joita voidaan hyödyntää osana sementtimäisiä materiaaleja, joista tämän väitöskirjan kannalta keskeisimmät ovat alkaliaktivoidut materiaalit (AAM) ja sementtiä korvaavat materiaalit (SCM). Tässä työssä keskitytään selluteollisuuden tuottamien soodakattilan lentotuhkan (RBA) sekä viherlipeäsakan (sakka) tutkimiseen. Tavoitteena oli selvittää, toimivatko nämä vaihtoehtoisena alkaliaktivaattorina, sillä yleisesti AAM:ssa käytetyt kemikaalipohjaiset aktivaattorit nostavat AAM:n

ympäristökuormaa. RBA:t käytettiin sellaisenaan. Sakkanäytteitä vastaanotettiin kolmessa erässä, ja näistä tehtiin kolme kokoomanäytettä, jotka lämpökäsiteltiin ennen käyttöä (105 °C, 300 °C, 525 °C tai 650 °C).

Tulosten mukaan RBA:t ja sakat aktivoivat masuunikuonapohjaista AAM:ää. Natriumsulfaattirikkaat RBA:t osoittivat vastaavia tai parempia aktivoivia ominaisuuksia kuin verrokkina toiminut kaupallinen natriumsulfaatti. Hydrataation aikana muodostui myös tyypillisiä hydrataatiotuotteita. Tulosten perusteella sopiva RBA:n annostus on 1–3 m-% (Na2O-ekv). Sakan lämpökäsittelyn (Tmax 525 °C) havaittiin muokkaavan materiaalin ominaisuuksia, muun muassa vähentämällä orgaanisen jäännöshiilen määrää sekä nostamalla liukoisen kalsiumin määrää. Liukoisen kalsiumin määrän noustessa myös pH kohosi. Kiteisen CaCO3:n lisäksi näytteistä havaittiin monimutkaisia magnesiumrikkaita faaseja, jotka sisälsivät ainakin hydrotalsiitin kaltaisia kerrostuneita kaksoishydroksideja (LDH).

Käsittelylämpötilan nostaminen 525 °C:seen paransi sakan aktivoivaa vaikutusta, joskin korkeimmat lujuudet 28 päivän iässä mitattiin, kun sakka oli käsitelty 300 °C:ssa. Kun lämpökäsiteltyä sakkaa kokeiltiin SCM:nä 25 % korvausosuudella, havaittiin, että 90 päivän lujuudet putosivat yli 15 %. Molemmissa systeemeissä (AAM ja SCM) sakan lisääminen nosti näytteen viskositeettia ja heikensi työstettävyyttä. Vaikutus kuitenkin pieneni, kun sakan käsittelylämpötilaa nostettiin. Yksi mielenkiintoisimmista tuloksista oli, että LDH-faaseja löydettiin myös niistä hydratoituneista näytteistä, joissa oli käytetty 525 tai 650 °C:ssa käsiteltyä sakkaa. Tämä viittaa siihen, että nämä faasit ovat uudelleenmuodostuneet lämpökäsittelyn jälkeen. Väitöskirjan tulokset osoittavat, että aiemmin inerttinä pidetyllä sakalla on aktivoivia ominaisuuksia.

- **Solidification/stabilization of an extremely heavy metals rich industrial side stream with ettringite-rich solid binders/ Piekkari, Katri 2024**

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  Contamination of the environment by heavy metals and other harmful elements from different industrial activities is a major issue globally. One common method to prevent this contamination is mixing harmful waste with ordinary Portland cement (OPC) in order to form a solid block from which the harmful components cannot escape. However, the large carbon footprint of OPC has created interest in finding ways to replace it in different applications.

  The aim of this thesis was to test new binders for the immobilization, i.e., solidification/stabilization (S/S), of several harmful ionic compounds at once. An industrial side stream (FS) with exceptionally high contents of several hazardous components: Pb, Hg, Se, As, Cd, Cr, Cu, Ni, and Zn, was immobilized using two different CSAB clinkers, mayenite, and ladle slag (LS), all used with gypsum and

water to achieve a high ettringite content. Ettringite can chemically incorporate different ions into its structure, enhancing the S/S. The leaching of the heavy metals was tested in water for 24 h and compared to the legal limit values for landfilled waste in Finland.

During testing the following harmful components were entirely immobilized in all scenarios: As, Cd, Cr, Cu, Ni, and Zn. Hg was successfully immobilized in most samples despite its high content in FS and low legal limit for leaching. The CSAB clinkers worked best for Pb and Hg immobilization, but had difficulty containing SO4 and Se. To counter this, the total sulfate content of the binder-FS mixture was reduced through two methods: replacing gypsum with Ca(OH)2 and using mayenite-based binders. This approach did reduce the leaching of SO4 and Se, but it also caused some issues for setting the binders. The incorporation of the contaminants into the immobilized solid samples was mostly encapsulation, whereas chemical incorporation into ettringite was observed for Se.

Several parameters were tested for their effect on the solidification of the binders and the S/S of the contaminants. Most noteworthily, citric acid can be used as a retarder to adjust the setting time of LS binders without compromising immobilization as long as the Ca(OH)2 content is kept low.

Ympäristön saastuminen erilaisista teollisuuden toiminnoista peräisin olevilla raskasmetalleilla ja muilla haitallisilla alkuaineilla on maailmanlaajuisesti merkittävä ongelma. Haitallisen jätteen sekoittaminen Portland-sementtiin (OPC) ja kovettaminen betonin sisään on yleinen ratkaisu, jolla vähennetään haitallisten kemikaalien päätymistä ympäristöön. OPC:lla on kuitenkin suuri hiilijalanjälki, minkä vuoksi sille etsitään korvaavia materiaaleja eri sovelluskohteissa.

Tämän väitöskirjan tavoitteena oli testata uusia materiaaleja haitallisen jätemateriaalin käsittelyyn käyttäen teollisuuden sivuvirtaa (FS), joka sisältää poikkeuksellinen suurina pitoisuuksina useita haitallisia alkuaineita: Pb, Hg, Se, As, Cd, Cr, Cu, Ni ja Zn. Tarkoitukseen käytettiin kahta eri CSAB-klinkkeriä, mayeniittia ja jatkuvavalukuonaa (JVK), joista kukin kovettuu kipsin ja veden kanssa reagoidessaan betoninkaltaiseksi sidosaineeksi, joka sisältää paljon ettringiitti-mineraalia. Ettringiitti pystyy sitomaan kemialliseen rakenteeseensa erilaisia ioneita, tehostaen niiden sitoutumista materiaaliin. Käsittelyn jälkeen haitallisten komponenttien liukoisuus testattiin vedessä 24 h ajan ja sitä verrattiin Suomen Kaatopaikka-asetuksessa jätteelle määritettyihin raja-arvoihin.

Kokeissa havaittiin, että As, Cd, Cr, Cu, Ni ja Zn sitoutuivat täysin kaikilla sidosaineilla. Hg sitoutui onnistuneesti useimmissa tapauksissa, vaikka sen pitoisuus FS:ssä oli suuri, ja sallitun liukeneman raja matala. CSAB-klinkkerit

sitoivat parhaiten Pb:ä ja Hg:a, mutta huonommin SO4:a ja Se:ä. Tämän vuoksi SO4:n kokonaispitoisuutta alennettiin kahdella tavalla: korvaamalla sidosaineessa käytettyä kipsiä Ca(OH)2:lla, ja siirtymällä käyttämään mayeniitti-pohjaisia sidosaineita (mayeniitti ja JVK). Näillä keinoin SO4:n ja Se:n liukoisuus saatiin laskemaan, mutta sidosaineiden kovettuminen kärsi. Haitallisten alkuaineiden sitoutuminen tapahtui pääasiassa sidosaineeseen kapseloitumalla, mutta Se:llä havaittiin myös sitoutumista ettringiittiin.

Työssä tutkittiin lisäksi sidosaineen koostumuksen merkitystä haitta-aineiden sitoutumiselle. Merkittävin havainto oli, että sitruunahapon avulla voidaan muokata JVK:n kovettumisaikaa ilman, että sitoutuminen kärsii, kunhan Ca(OH)2:n määrä on matala.

- **Highly porous alkali activated foams for water and wastewater treatment/ Bhuyan, Mohammad 2024**

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  Alkali-activated materials (AAMs) have diverse applications in water and wastewater treatment. In this thesis, porous AAM foams were prepared with the goal to explore their potential use in new applications for water and wastewater treatment, namely adsorptive filters, point-of-use water disinfection, and separation of microplastics.

  The adsorptive filters were prepared from blast furnace slag and optimized by comparing five different surfactants and doses of H2O2. Porous AAM exhibiting the highest mechanical strength was investigated for methylene blue adsorption. To further enhance the adsorption performance, a lignin-containing composite foam was prepared. In the dynamic adsorption experiments, the highest adsorption amount obtained with the lignin-composite foam was ~40 mg/g. Moreover, peracetic acid was investigated as an alternative foaming agent in the preparation of porous AAMs. During the investigation, lower volume expansion and faster reaction kinetics with reduced setting time were observed for peracetic acid-based porous AAM compared to H2O2-based porous AAM.

  To develop material for point-of-use water disinfection, the first goal was to achieve comparable water permeability to traditional ceramic filters by varying the amount of hydrogen peroxide. An optimized foam was then treated with colloidal Ag solution to explore its potential use in disinfecting water for 10 weeks. The modified foam demonstrated a significant reduction (2.84 log10 units) in E. coli bacteria compared to an unmodified filter (1.57 log10 units). Additionally, the environmental impact of the porous AAM was analyzed through life cycle assessment and found to be lower than that of conventional ceramic filter.

Finally, to develop material capable of separating microplastics, porous AAM surface was modified with triethoxy(octyl)silane to render it superhydrophobic. The modified porous AAM demonstrated over 99% separation efficiency when treating 30 L of model water containing 5 mg/L of polyethylene microspheres (53-63 µm). Its performance was also evaluated in treating laundry effluent, where the modified porous AAM achieved approximately 84% separation compared to around 52% for the unmodified porous AAM.

Alkaliaktivoiduilla materiaaleilla on runsaasti erilaisia sovelluksia veden ja jäteveden käsittelyssä. Tässä väitöskirjassa valmistettiin huokoisia alkaliaktivoituja vaahtoja tavoitteena selvittää niiden uusia hyödyntämismahdollisuuksia adsorboivina suodatinmateriaaleina, veden desinfioinnissa ja mikromuovin erottamisessa.

Masuunikuonasta valmistettujen adsorboivien suodattimien koostumus optimoitiin muuttamalla valmistuksessa käytetyn pinta-aktiivisen aineen tyyppiä sekä vaahdotinaineena toimivan vetyperoksidin lisäysmäärää. Optimoidulla materiaalilla tutkittiin metyleenisinisen adsorptiota vedestä. Adsorptiokyvyn lisäämiseksi valmistettiin ligniiniä sisältävää komposiittimateriaalia. Dynaamisessa metyleenisinisen adsorptiokokeessa suurin adsorptiomäärä ligniinikomposiitille oli ~40 mg/g. Lisäksi peretikkahappoa tutkittiin vaihtoehtoisena vaahdotusaineena. Peretikkahappoa käytettäessä havaittiin pienempi turpoaminen valmistuksen aikana ja lyhyempi kovettumisaika verrattuna vetyperoksidilla valmistettuihin vaahtoihin.

Tutkimuksen seuraavassa osassa tutkittiin veden desinfiointia. Alkaliaktivoituja vaahtoja valmistettiin metakaoliinista, masuunikuonasta ja niiden seoksista tavoitteena saavuttaa samanlainen veden läpäisevyys kuin keraamisilla suodattimilla. Tämän jälkeen optimoitua vaahtoa käsiteltiin kolloidisella hopealiuoksella ja sen käyttömahdollisuuksia veden desinfioinnissa tutkittiin 10 viikon ajan. Hopeaa sisältävä vaahto osoitti merkittävää E. coli -bakteerien vähenemistä (2,84 log10) verrattuna hopeaa sisältämättömään suodattimeen (1,57 log10). Lisäksi alkaliaktivoidun vaahdon ympäristövaikutuksia analysoitiin elinkaariarvioinnin avulla ja niiden todettiin olevan pienempiä kuin perinteisen keraamin.

Mikromuovien erottamiseksi alkaliaktivoituja vaahtoja käsiteltiin trietoksi(oktyyli)silaanilla superhydrofobisen pinnan luomiseksi. Käsitelty vaahto poisti yli 99 % mikromuovista kokeessa, jossa käsiteltiin 30 litraa vettä, joka sisälsi 5 mg/l polyetyleenipartikkeleita (koko 53–63 µm). Käsitellyn vaahdon suorituskykyä arvioitiin myös pyykinpesuveden käsittelyssä, jossa sen muovin poistokyky oli noin 84 % kun taas ei-käsitelty vaahto poisti vain 52 %.

- **Recycling and reusing of waste concrete fines as granulated aggregates/ Kursula, Kalle 2024**

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  In recent years, a large amount of construction and demolition waste has been generated by many demolition and construction projects because of fast urbanization. There is therefore a growing need for the sustainable management of construction waste and its recycling. The fine fraction of construction waste is especially challenging to reuse, and the problem is that it is yet to be fully utilized.

  Current options for the recycling of recycled concrete fines are limited, and there is a lack of research related to this. Today, recycled concrete fines are typically dumped in landfill, which requires large areas and may cause environmental contamination through water and soil pollution. The recycling and utilization of recycled concrete fines could make a significant contribution to sustainable development and the environment.

  This thesis, examined the possibility of the utilization of the recycled concrete fines. The general aim was to produce artificial aggregates from different recycled concrete fines by granulation.

  The results of this thesis show that with suitable co-binders and curing methods, it is possible to produce artificial aggregates from recycled concrete fines that have comparable engineering properties as commercial lightweight aggregates.

  Most of the produced artificial aggregates can be classified as lightweight aggregates according to the EN 13055-1 standard. It was observed that the strength of the produced aggregates was highly dependent on their reactivity, particle size, and the different co-binders and curing methods used. The lightweight concrete produced from these artificial aggregates showed almost similar strength to lightweight concrete produced from commercial lightweight aggregate.

  Kaupungistuminen on johtanut viime vuosina moniin rakennus- ja purkuprojekteihin, joka on tuottanut valtavan määrän erilaista rakennus- ja purkujätettä. Näin ollen rakennus- ja purkujätteen kierrättämiselle ja ympäristöystävälliselle uudelleenkäytölle on kasvavaa kysyntää. Erityisesti betonijätteestä syntyvä hienoaines on haastavaa kierrättää ja ongelmana on, ettei sitä pystytä täysin hyödyntämään.

  Nykyiset vaihtoehdot jätebetonijauheen kierrättämiselle ovat vähäiset ja tutkimusta sen hyödyntämisestä on tehty vähän. Yleensä jätebetonin hienoaine on viety kaatopaikalle, mikä vaatii suuria maapinta-aloja ja on ympäristölle haitallista sillä se

saattaa saastuttaa maaperää ja luonnonvesiä. Näin ollen jätebetonijauheen hyödyntämisellä olisi suuria etuja kestävän kehityksen ja ympäristön kannalta.

Tässä väitöskirjassa tarkoituksena on tutkia jätebetonin hienoaineksen hyödyntämismahdollisuuksia. Erityinen tavoite oli tuottaa aggregaatteja erilaisista jätebetonijauheista rakeistusprosessin avulla.

Väitöskirjan tulokset osoittavat, että sopivien sideaineiden ja kovetusmenetelmien avulla on mahdollista tuottaa jätebetonijauheesta aggregaatteja, joilla on vertailukelpoiset ominaisuudet kaupallisen kevytsoran kanssa.

Suurin osa tuotetuista aggregaateista voidaan luokitella kevytsoraksi standardin EN 13055-1 mukaan. Tutkimuksessa havaittiin, että tuotettujen aggregaattien lujuus riippui suuresti käytetyn betonijauheen reaktiivisuudesta ja partikkelikoosta, sekä käytetystä sideaineesta ja kovetusmenetelmästä. Näillä aggregaateilla valmistettujen kevytbetonien lujuus oli vertailukelpoinen kaupallisella kevytsoralla valmistettuun betoniin.

- **Alkali activation of iron-rich fayalite slag : fresh, hardened and durability properties/ Adediran, Adeolu Idowu 2023**

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  Fayalite slag (FS) is an Fe-rich by-product generated during non-ferrous metallurgy refining processes. Currently, the annual global production of FS is 58 million tons, and this is likely to increase soon due to the increasing demand for non-ferrous metals for varied applications. Regrettably, only a small fraction of FS is utilized in low value applications with most of it ending up in landfills. The aim of this thesis is to fully utilize FS as precursor for alkali-activated materials (AAMs). AAMs are alternative cementitious materials that could provide environmental benefits compared to Portland cement concrete.

  Although FS contains a large amount of iron (>50%) and low amounts of calcium, aluminium, and amorphous material compared to blast furnace slag, which is a commonly used AAM precursor, the results of this thesis show that this low reactive material can be used as a sole precursor (aggregate and binder source) for AAMs. Furthermore, the mineralogical investigation of different particle size fractions of FS revealed a variation in the amorphous content. Fine fractions of FS had a higher amorphous content, and this resulted in higher reactivity and better mechanical and microstructural properties compared to the coarse fractions of FS.

  AAMs containing FS as an aggregate and binder had superior mechanical and microstructural properties compared to those containing standard sand as

aggregates. Further optimization of the particle size distribution and elevated temperature curing improved the properties of FS-based AAMs. To avoid the use of curing at elevated temperatures, the incorporation of co-binders into the FS matrix was investigated as a means to improve the properties of FS-based AAMs at an ambient temperature and facilitate their practical application. The incorporation of co-binders significantly modified the gels formed and improved the fresh, hardened and durability properties of FS-based AAMs when exposed to different aggressive environmental conditions and high temperature. The outcome of this thesis work can provide detailed information on the full utilization of FS with high potential for construction applications.

Fayaliittikuona on ei-rautametallien jalostusprosesseissa syntyvä rautapitoinen sivutuote. Tällä hetkellä fayaliittikuonaa tuotetaan maailmanlaajuisesti 58 miljoonaa tonnia, ja määrän odotetaan kasvavan ei-rautametallien kysynnän lisääntyessä erilaisissa sovelluksissa. Vain pieni osuus fayaliittikuonasta pystytään hyödyntämään vähäarvoisissa sovelluksissa suurimman osan päätyessä kaatopaikoille. Tämän väitöskirjan tavoitteena on hyödyntää fayaliittikuonaa kokonaisvaltaisesti alkaliaktivoitujen materiaalien (AAM) raaka-aineena. AAM:t ovat vaihtoehtoisia sementtipohjaisia materiaaleja, jotka voivat tarjota ympäristöhyötyjä portlandsementtibetoniin verrattuna.

Fayaliittikuona sisältää suuren määrän rautaa (>50 %) ja vähän kalsiumia, alumiinia sekä amorfista ainetta verrattuna masuunikuonaan, joka on yleisesti käytetty AAM:ien raaka-aine. Tämän väitöskirjatyön tulokset kuitenkin osoittavat, että tätä matalareaktiivista fayaliittikuonaa voidaan käyttää sekä aggregaattina että sideaineena AAM-laasteissa. Lisäksi fayaliittikuonan eri kokojakeiden mineraloginen tutkimus paljasti vaihtelua amorfisessa aineen määrässä. Pienien fayaliittikuonapartikkelien amorfinen pitoisuus oli korkeampi kuin isojen partikkelien, mikä johti pienen kokojakauman korkeampaan reaktiivisuuteen sekä sideaineen parempiin mekaanisiin ja mikrorakenteellisiin ominaisuuksiin. Fayaliittikuona sisältää suuren määrän rautaa (>50 %) ja vähän kalsiumia, alumiinia sekä amorfista ainetta verrattuna masuunikuonaan, joka on yleisesti käytetty AAM:ien raaka-aine. Tämän väitöskirjatyön tulokset kuitenkin osoittavat, että tätä matalareaktiivista fayaliittikuonaa voidaan käyttää sekä aggregaattina että sideaineena AAM-laasteissa. Lisäksi fayaliittikuonan eri kokojakeiden mineraloginen tutkimus paljasti vaihtelua amorfisessa aineen määrässä. Pienien fayaliittikuonapartikkelien amorfinen pitoisuus oli korkeampi kuin isojen partikkelien, mikä johti pienen kokojakauman korkeampaan reaktiivisuuteen sekä sideaineen parempiin mekaanisiin ja mikrorakenteellisiin ominaisuuksiin.

Fayaliittikuonaa aggregaattina ja sideaineena sisältävillä laasteilla oli ylivoimaiset mekaaniset ja mikrorakenteelliset ominaisuudet verrattuna laasteihin, jotka sisälsivät aggregaattina tavallista hiekkaa. Lisäksi partikkelikokojakauman

optimointi ja kovettaminen korkeassa lämpötilassa paransivat laastien mekaanisia ominaisuuksia. Korkeassa lämpötilassa kovettamista pyrittiin välttämään tutkimalla, voitaisiinko fayaliittikuonapohjaisten laastien kovettumista parantaa lisäämällä rinnakkaissideaineita. Seosaineiden käyttö muutti merkittävästi muodostuneita sideainegeelejä ja paransi laastien tuoreita, kovettuneita ja kestävyysominaisuuksia, kun ne altistettiin erilaisille aggressiivisille ympäristöolosuhteille ja korkeille lämpötiloille. Tämän väitöskirjatyön tulokset tarjoavat yksityiskohtaista tietoa fayaliittikuonan kokonaisvaltaisesta hyödyntämisestä ja sen mahdollisuuksista rakentamisen eri sovelluksissa.

- **Alternative ye'elimite (CSA) cement clinkers from industrial byproducts/ Isteri, Visa 2023**

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  The production of ordinary Portland cement (OPC) is responsible for ~8% of global anthropogenic CO_2. Two thirds of the emissions arise from the calcination of limestone ($CaCO_3$ -> CaO + CO_2). Meanwhile, huge volumes of inorganic industrial sidestreams with necessary ingredients for cement production (Al_2O_3, CaO, SiO_2, and Fe_2O_3) are landfilled across the globe. Locally these raw materials can be used to replace virgin raw materials of cement manufacture and provide a source of already decarbonized CaO that can reduce the carbon footprint of cement manufacture while promoting the circular economy. The driving factors for industry to utilize their industrial sidestreams are to find a way to enhance waste valorization, to cover the rising expenses of landfilling due to taxation and regulations, and to tackle resource scarcity.

  The aim of this thesis is to utilize Finnish metallurgical slags (argon oxygen decarburization (AOD) slag, ladle slag (LS), fayalitic slag (FS), burned jarosite slag (Fe slag)), and phosphogypsum (PG) which is a byproduct of fertilizer production as a raw material source for the production of two alternative ye'elimite (CSA) cement clinkers; CSAB (calcium sulfoaluminate belite), and AYF (alite-ye'elimite-ferrite). The chemical composition of ye'elimite clinkers requires less calcium than conventional OPC and allows the use of sulfur- and aluminum-containing raw materials. To allow the use of iron-containing slags, the produced clinkers had a high ferrite phase content. The main concern to use industrial sidestreams as raw materials are the impurities that may affect the clinkering parameters and mineralogy. Detailed microstructural analyses were performed on the clinker to reveal the clinker composition, as well as the partition of the minor elements. The usability of the raw materials for cement manufacture was first tested in laboratory-scale experiments and was then translated to a pilot demonstration in a 7-meter semi-industrial kiln.

It was found through mineralogical analysis that impurities from raw materials affected the produced clinker phases in both clinker types when compared to natural raw materials. CSAB clinker was found to be successful in a pilot demonstration. The raw meal of pilot CSAB was composed of 85% industrial residues, and the CO_2 emissions caused by chemical reactions were 90% lower than that of PC cement made with virgin raw materials. CSAB clinker from pilot demonstration was mixed with anhydrite, sand, and water to make concrete mortars that led to 28-day performance equaling reference PC cement (CEM II/B-M (S-LL) 42,5 N). AYF clinker was successfully produced in laboratory conditions, but the use of fluorine-containing AOD slag was found challenging in a pilot-scale demonstration and requires further experiments.

Sementtiteollisuus aiheuttaa 8 % kaikista ihmisen aiheuttamista CO_2 päästöistä, joista kaksi kolmasosaa (2/3) syntyy kalkkikiven kalsinoinnista ($CaCO_3$ -> CaO + CO_2). Samanaikaisesti teollisuus tuottaa maailmanlaajuisesti suuret määrät läjitettäviä epäorgaanisia jätemateriaaleja, joiden sisältämät alkuaineet (Al_2O_3, CaO, SiO_2 ja Fe_2O_3) sopivat sementin raaka-aineeksi. Paikallisesti näitä materiaaleja voitaisiin hyödyntää sementin valmistuksessa, ne tarjoavat lähteen CO_2 vapaalle kalkille (CaO), joka voisi alentaa sementin valmistuksen CO_2 päästöjä samalla edistäen kiertotaloutta. Tiukentuva lainsäädäntö ja verotus läjitettävälle jätteelle on ajava voima yrityksille löytää keinoja hyödyntää ja tuotteistaa jätemateriaaleja.

Väitöskirjatutkimuksessani tutkin ye'elimiitti (kalsiumsulfoaluminaatti eli CSA) pitoisten sementtien valmistusta hyödyntäen metallurgisen teollisuuden kuonia (AOD-kuona, senkkakuona, fayaliittikuona ja pyrometallurgisesti käsitelty jarosiittikuona), sekä fosforilannoitteen valmistuksessa syntyvää fosforikipsiä. Vaihtoehtoiset sementit nimetään yleisesti niissä ilmenevien pääminerаalien mukaan. Tässä työssä valmistetut vaihtoehtoiset sementtiklinkkerit ovat CSAB (ye'elimiitti-beliitti) ja AYF (aliitti-ye'elimiitti-ferriitti). Tutkimuksessa kehitettyjen CSA-sementtien perusidea on korvata perinteisen sementin pääminerаaleja alhaisemman kalkkipitoisuuden omaavilla mineraaleilla, joka mahdollistaa sulfaatti-, rauta- ja alumiinioksidipitoisten jätemateriaalien monipuolisen käyttämisen raaka-aineena. Työssä valmistetut sementit sisälsivät tavanomaista sementtiä korkeamman pitoisuuden rautapitoista brownmilleriitti (ferriitti) mineraalia, joka mahdollisti rautapitoisten kuonien käytön. Jätemateriaalien sisältämien epäpuhtauksien vaikutusta sementtiklinkkerin mikrorakenteeseen ja muodostuviin mineraaleihin tutkittiin monipuolisesti. Jätemateriaalien käyttöä sementin raaka-aineina tutkittiin aluksi laboratoriomittakaavassa, jonka jälkeen valmistusta kokeiltiin 7-metrisessä pilottimittakaavan jatkuvatoimisessa sementtiuunissa. Mineralogisissa analyyseissä huomattiin, että jätemateriaalien epäpuhtaudet johtivat muutoksiin valmistettujen sementtiklinkkerien mineralogiassa ja mineraaleissa verrattaessa puhtaista raaka-aineista valmistettuihin verrokkeihin.

CSAB-klinkkerin valmistus onnistui laboratoriossa ja pilottimittakaavassa. Valmistetussa sementtiklinkkerissä parhaimmillaan 85 % raaka-aineista oli korvattu teollisuuden jätemateriaaleilla ja raaka-aineista peräisin olevat CO_2-päästöt alenivat 90 % verrattuna kalkkikivestä valmistettuun OPC-sementtiklinkkeriin. CSAB-sementtiklinkkeristä, anhydriitistä ($CaSO_4$), vedestä ja hiekasta valmistettujen betonikappaleiden 28 päivän lujuusominaisuudet vastasivat kaupallisen OPC-sementin (CEM II/B-M (S-LL) 42,5 N) lujuutta. AYF-sementtiklinkkereitä pystyttiin valmistamaan laboratorio-olosuhteissa, mutta pilottimittakaavassa fluoria sisältävän AOD-kuonan käyttö osoittautui vaikeaksi ja vaatisi lisätutkimusta.

- **Cementitious binders for construction in northern cold regions/ Alzaza, Ahmad 2023**

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  The construction season in northern regions is shortened by the severe cold weather, which also considerably reduce the performance and quality of cementitious materials. The construction season is currently extended using various methods, such as the installation of heating/insulation systems, the use of high-early-strength cement, and the avoidance of the use of ecofriendly supplementary cementitious materials (SCMs). These measures increase the costs, energy consumption, emissions, and complexity of winter construction. Winter maintenance work is consequently postponed frequently, thereby decelerating regional growth. Therefore, this thesis aims to develop sustainable cementitious materials for northern cold regions with maximum utilization of SCMs and minimum use of heating systems.

  A comparable 28-day compressive strength can be attained in the ordinary Portland cement (OPC)-based binder cured at −10 °C to that at 20 °C, which can be attributed to the combined effects of calcium silicate hydrate (C–S–H) seeds, a binary antifreeze admixture, and room-temperature (23 °C ± 1 °C) precuring. Moreover, 30 wt.% of OPC in the 0 °C-cured binders could be substituted with ground granulated blast-furnace slag by the addition of C–S–H seeds. This replacement level can be increased to 50 wt.% with the use of GGBFS pre-alkali activation treatment. The calcium sulfoaluminate belite ferrite (CSABF) cement works effectively as an ecofriendly mineral accelerator, assuring the strength development of the OPC/CSABF blend at extremely low ambient temperatures (i.e., −25 °C). The results of this thesis demonstrate the potential for extending the construction season in northern regions using more sustainable cementitious materials while reducing the requirement for expensive and energy-consuming heating systems during winter construction work.

Pohjoisten alueiden rakennuskautta lyhentää ankara kylmä sää, joka myös heikentää huomattavasti betonin laatua. Rakennuskautta pidennetään tällä hetkellä erilaisilla menetelmillä, kuten lämmitys-/eristysjärjestelmien asennuksella, korkean varhaisen lujuuden omaavan sementin käytöllä ja sementtiä korvaavien materiaalien (SCM) käytön välttämisellä. Nämä toimenpiteet lisäävät talvirakentamisen kustannuksia, energiankulutusta, ja CO2-päästöjä, ja monimutkaistavat rakentamista. Näin ollen talvikrakentamista lykätään usein, mikä hidastaa alueellista kasvua. Siksi tämän opinnäytetyön tavoitteena on kehittää kestäviä sementtimäisiä sideaineitaa pohjoisille kylmille alueille hyödyntämällä mahdollisimman paljon sementtiä korvaavia ympäristöystävällisiä sideaineita ja käyttämällä mahdollisimman vähän lämmitysjärjestelmiä.

Tavalliselle, Portland-sementtipohjaiselle (OPC) sideaineelle voidaan saavutta yhtä korkea lujuus −10 °C:ssa kuin 20 °C:ssa 28 päivän iässä, jos käytetäään kalsiumsilikaattihydraatti (C–S–H) -nanopartikkeleita, jäätymisenestoaineita ja esikovetusta huoneenlämpötilassa (23 °C ± 1 °C). Lisäksi 0 °C:ssa kovettuneissa sideaineissa 30 paino-%:a OPC:sta voitaisiin korvata jauhetulla masuunikuonalla lisäämällä siihen C–S–H-nanopartikkeleita. Tämä korvausaste voidaan nostaa 50 paino-%:iin käyttämällä masuunikuonan alkaliaktivaatiokäsittelyä. Lisäksi työssä havaittiin, että kalsiumsulfoaluminaattibeliitti-ferriittisementti (CSABF) toimii tehokkaasti ympäristöystävällisenä mineraalikiihdyttimenä ja varmistaa OPC/CSABF-seoksen lujuuskehityksen erittäin alhaisissa ympäristön lämpötiloissa (−25 °C). Tämän opinnäytetyön tulokset osoittavat, että rakennuskautta on mahdollista pidentää pohjoisilla alueilla kestävämmillä sementtimateriaaleilla ja samalla vähentää kalliiden ja energiaa kuluttavien lämmitysjärjestelmien tarvetta talvibetonoinnin aikana.

- **Advanced high and low field ¹H and ¹²⁹Xe NMR methods for studying polymerization, curing and pore structures of geopolymers/ Li, Jing 2022**

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  Geopolymers are three-dimensional aluminosilicate frameworks, synthesized from the aluminosilicate sources activated by alkali solutions under mild conditions. They are widely regarded as sustainable construction materials.
  The understanding of geopolymer pore structures is important for their development. The mechanical properties of geopolymers depend on their pore structures. Currently, the pore structures are often studied using destructive methods, which cannot be used in longitudinal studies. Thus, new methods are required to characterize the time-dependent properties of geopolymers.

  In this thesis, the following advanced ^{1}H and ^{129}Xe nuclear magnetic resonance (NMR) methods were applied to study the polymerization, curing, and pore structure

of geopolymers: ^{1}H relaxometry, ^{1}H cryoporometry, ^{129}Xe spectroscopy, and ^{129}Xe relaxometry. As a result, several interconnected mesopores with different pore sizes were found. Additionally, three factors were found to affect the geopolymerization and pore structures: water-to-solid ratio (*w/s*), silicon-to-aluminum ratio (*Si/Al*), and NH_4OH posttreatment. High *w/s* favors large pore sizes and enhanced pore connectivity. Low *Si/Al* = 1 contributes to the formation of the zeolite phase, resulting from the formation of a gel phase with low *Si/Al* during geopolymerization. The NH_4OH posttreatment did not change pore sizes, but it did increase the level of pore connectivity.

Geopolymeerit ovat kolmiulotteisia alumiinisilikaattirakenteita, jotka syntetisoidaan alumiinisilikaattilähteistä, jotka aktivoidaan alkaliliuoksella miedoissa olosuhteissa. Niitä pidetään laajalti ympäristöystävällisinä rakennusmateriaaleina. Geopolymeerihuokosrakenteiden ymmärtäminen on tärkeää niiden sovellusten kannalta. Geopolymeerien mekaaniset ja absorptio ominaisuudet riippuvat niiden huokosrakenteista. Tällä hetkellä huokosrakenteita tutkitaan yleensä destruktiivisilla menetelmällä, jolloin pitkittäistutkimus ei ole mahdollista. Tämän vuoksi geopolymeerien ajasta riippuvien ominaisuuksien karakterisointiin tarvitaan uusia menetelmiä.

Tässä väitöskirjassa geopolymeerien polymeroitumisen, kovettumisen ja huokosrakenteen tutkimiseen sovellettiin edistyneitä ^{1}H- ja ^{129}Xe NMR-menetelmiä: ^{1}H-relaksometriaa, ^{1}H-kryoporometriaa, ^{129}Xe-spektroskopiaa ja ^{129}Xe-relaksometriaa. Tutkimuksessa löydettiin useita toisiinsa liittyneitä mesohuokosia, joiden huokoskoko oli erilainen. Tutkimuksessa huomattiin, että geopolymeerien polymeroitumiseen ja huokosrakenteeseen vaikuttaa kolme tekijää: vesi/kiintoainesuhde (*w/s*), pii/alumiini suhde (*Si/Al*) ja jälkikäsittely NH_4OH:lla. Suuri *w/s* suosii suuria huokoskokoja ja parantaa huokosten kytkeytyneisyyttä. Matala *Si/Al* = 1 edistää zeoliittifaasin muodostumista, mikä johtuu sellaisen geelifaasin muodostumisesta, jossa on alhainen *Si/Al* geopolymeroinnin aikana. NH_4OH-jälkikäsittely ei muuttanut huokoskokoa, mutta lisäsi huokosten kytkeytyneisyyttä.

- **Valorization of mining wastes in alkali-activated materials/ Niu, He 2022**

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  The mining industry can generate wastes from excavation and mineral processing, namely waste rock, and mine tailings, which poses potential environmental ricks worldwide. The European Union mining industries have discarded their waste residues for more than 100 years. It is estimated that almost 65% of the waste produced in the EU is mineral waste. Large amounts of waste rock and tailings are stored in stockpiles and tailing impoundments without further exploration. Small

portions of these wastes are utilized as fillers or backfills with cement pastes. The challenge lies in how to valorize those underutilized side streams, turning mining waste issues into a secondary raw materials opportunity. Alkali-activated materials are alternative cementitious materials with a lower carbon footprint than traditional Portland cement. The typical raw precursor, calcined kaolin (metakaolin), is rich in aluminosilicates, generating a three-dimensional framework under alkali conditions. Mining wastes, that contain aluminosilicate minerals are potential precursors for alkali activation. In contrast to calcined kaolin, mining wastes containing aluminosilicate-bearing minerals can be chemically inert and cannot be directly used as precursors. This requires enhanced chemical reactivity or mixing with other reactive raw materials.

The aim of this work was to investigate the potential of using mining wastes as secondary raw materials for alkali activation and valorizing waste rock and mine tailings in alkali-activated materials. It focuses on enhancing the chemical reactivity of mining wastes via a potentially greener approach (mechanochemical activation) compared to the calcination. Mechanochemical activation was implemented on both mine tailings and waste rock. Further, mine tailings are incorporated with metakaolin and blast furnace slag to produce alkali-activated tailing co-binders. The role of tailings in final alkali-activated materials was also investigated using diverse characterization methods.
The phlogopite and carbonate-bear phosphate mine tailings and muscovite-bearing sulfidic waste rock were subjected to mechanochemical activation, and they generated amorphous phases, which yielded a higher alkaline dissolution. The sole mine tailings or waste rock-based alkali-activated materials were successfully synthesized. Incorporation of mine tailings in alkali-activated co-binders, such as metakaolin and blast furnace slag, can significantly affect the hydration process, alkali activation, and physical performance. The role of tailings in alkali-activated materials is complicated, especially after mechanochemical activation. The amorphous part of phosphate mine tailings participates in alkali activation, forming C-(N)-A-S-H and other zeolites. Although sulfidic mine tailings contain only crystalline substances, they considerably alter the hydration and porosity of the final products.

Kaivosteollisuuden louhinta- ja mineraalinkäsittelyprosessit tuottavat valtavia määriä jätettä, pääasiassa sivukiveä ja rikastushiekkaa. Euroopan unionin kaivosteollisuus on tuottanut näitä jätteitä jo yli 100 vuoden ajan, ja EU:ssa tuotetusta jätteestä lähes 65 %:n on arvioitu olevan mineraalijätettä. Sivukivet ja rikastushiekka varastoidaan pääasiassa läjittämällä ne rikastushiekka-altaisiin, ja vain pieni osa jätteistä hyödynnetään esimerkiksi täyteaineena sementtipastassa. Nämä alihyödynnetyt sivuvirrat voisivat kuitenkin toimia uusioraaka-aineena neitseellisten luonnonvarojen sijaan, mikä vähentäisi läjitykseen päätyvän jätteen määrää.

Alkaliaktivoidut materiaalit ovat vaihtoehtoisia sementtimäisiä materiaaleja, joilla on perinteistä portlandsementtiä pienempi hiilijalanjälki. Tyypillinen lähtöaine on kalsinoitu kaoliini (metakaoliini), joka sisältää runsaasti alumiinisilikaatteja, jotka reagoivat alkalisissa olosuhteissa lujittuvaksi materiaaliksi. Alumiinisilikaattimineraaleja sisältävät kaivosjätteet ovat potentiaalisia raaka-aineita alkaliaktivointiin. Toisin kuin kalsinoitu kaoliini, alumiinisilikaattia sisältävät kaivosjätteet ovat tyypillisesti kemiallisesti inerttejä, eikä niiden käyttö suoraan alkaliaktivoitujen materiaalien lähtöaineena ole mahdollista. Sen sijaan ne vaativat kemiallisen reaktiivisuuden parantamista tai sekoittamista muiden reaktiivisten raaka-aineiden kanssa.

Tämän työn tavoitteena oli tutkia mahdollisuuksia hyödyntää kaivosjätettä alkaliaktivoinnin lähtöaineena sekä kaivosjätteen hyödyntämistä alkaliaktivoiduissa materiaaleissa. Työ keskittyy kaivosjätteiden kemiallisen reaktiivisuuden parantamiseen mekanokemiallisella aktivoinnilla. Mekanokemiallista aktivointia sovellettiin sekä kaivoksen rikastusjätteeseen että sivukiveen. Lisäksi kaivoksen rikastushiekkaan yhdistettiin metakaoliinia ja masuunikuonaa, ja seoksesta valmistettiin alkaliaktivoituja materiaaleja. Rikastushiekan roolia lopullisissa alkaliaktivoiduissa materiaaleissa tutkittiin erilaisilla karakterisointimenetelmillä. Flogopiittia ja karbonaatteja sisältävää fosfaattirikastushiekkaa sekä muskoviittia sisältävää sulfidista sivukiveä aktivoitiin mekanokemiallisesti. Näin muodostui amorfista faasia, joka on lähtöainetta reaktiivisempi alkalisissa olosuhteissa. Käsitellyistä rikastushiekasta ja sivukivestä valmistettiin onnistuneesti alkaliaktivoituja materiaaleja. Kaivosjätteiden yhdistäminen muiden lähtöaineiden, kuten metakaoliinin ja masuunikuonan, paransi alkali aktivoidun materiaalin ominaisuuksia. Rikastushiekan rooli alkaliaktivoiduissa materiaaleissa on monimutkainen erityisesti mekanokemiallisen aktivoinnin jälkeen. Fosfaattisen rikastushiekan amorfinen osa voi osallistua alkaliaktivointiint muodostaen C-(N)-A-S-H:ta ja zeoliittirakenteita. Vaikka sulfidiset rikastusjätteet sisältävät vain kiteistä ainetta, myös se vaikuttaa alkaliaktivointireaktioihin ja lopputuotteen ominaisuuksiin.

- **Synthesis and alkali activation of magnesium-rich aluminosilicates/ Nellattukuzhi Sreenivasan, Harisankar 2021**

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  Alkali-activated materials (AAMs) are alternative cementitious materials with lower carbon footprints compared to traditional Portland cement (PC). In addition to Ca, Si, and Al, the precursors used in the preparation of AAMs can sometimes include considerable amounts of Mg, so that Mg significantly influences the structure and properties of AAMs. When compared to Ca, Si, and Al, relatively few studies have focused on the role of Mg in AAMs. This thesis deals with alkali activation of Mg-rich aluminosilicate precursors with the following objectives: 1) preparation, characterization, and estimation of alkaline reactivity of Na-Mg aluminosilicate

glasses; 2) synthesis of AAMs from Na-Mg aluminosilicate glasses and their detailed characterization to understand the fate of Mg; and 3) estimation of the potential of phlogopite as a Mg-rich raw material for alkali activation.

The structural study of Na-Mg aluminosilicate glasses indicates that the higher cationic field strength (CFS) of Mg than Na makes Mg preferable as a network modifier, whereas Na acts as a charge compensator. Alkaline reactivity studies of Na-Mg aluminosilicate glasses reveal that as Mg replaces Na in glasses, the reactivity of the glasses increases initially, attains a maximum, and then drops. This trend can be explained by the interplay between glass depolymerization and optical basicity: depolymerization dictates the glass reactivity initially, while the effect of optical basicity dominates at later stages. Detailed structural study of AAMs prepared from Na-Mg aluminosilicate glasses indicates that Mg in AAMs exists as an amorphous magnesium silicate (AMS) phase, but the existence of this phase is not well documented in the literature. The driving force for AMS formation is the high CFS of Mg, which leads to effective stabilization of the depolymerized silicate species. The absence of hydrotalcite-group phases from these AAMs is due to the depletion of Al by zeolite production. The assessment of phlogopite mineral as a Mg-rich precursor for alkali activation indicates that untreated phlogopite is highly inert. However, thermal treatment could enhance the alkaline reactivity of phlogopite.

Alkali -aktivoidut materiaalit (AAM) ovat vaihtoehtoisia sementtimateriaaleja, joilla on pienempi hiilijalanjälki verrattuna perinteiseen portland -sementtiin (PC). Ca: n, Si: n ja Al: n lisäksi esiasteissa (joita käytetään AAM: ien valmistukseen) voi joskus olla huomattava määrä Mg: tä, ja tämä johtaa siihen, että Mg vaikuttaa merkittävästi AAM: ien rakenteeseen ja ominaisuuksiin. Verrattuna Ca, Si ja Al, on ollut suhteellisen vähän tutkimuksia, joissa keskitytään Mg: n rooliin AAM: issä. Tämä opinnäytetyö käsittelee Mg-rikkaiden alumiinisilikaattiesiasteiden alkaliaktivaatiota seuraavilla tavoitteilla: 1) Na-Mg-alumiinisilikaattilasien alkalisen reaktiivisuuden valmistelu, karakterisointi ja arviointi; 2) synteesi AAM: istä Na-Mg-alumiinisilikaattilasista ja niiden yksityiskohtainen karakterisointi Mg: n kohtalon ymmärtämiseksi; 3) Flogopiitin potentiaalin arviointi Mg-rikkaana raaka-aineena alkalin aktivoimiseksi.

Na-Mg-alumiinisilikaattilasien rakennetutkimus osoittaa, että Mg: n korkeamman kationisen kentänvoimakkuuden (CFS) takia Na: n vuoksi Mg on edullinen verkon muokkaajana, kun taas Na toimii varauksen kompensoijana. Na-Mg-alumiinisilikaattilasien alkaliset reaktiivisuustutkimukset paljastavat, että kun Mg korvaa Na: n lasissa, lasien reaktiivisuus kasvaa aluksi ja saavuttaa maksimin, minkä jälkeen se laskee. Tämä suuntaus voidaan selittää lasin depolymeroinnin ja optisen emäksisyyden välisellä vuorovaikutuksella: depolymerointi sanelee aluksi lasin reaktiivisuuden, kun taas optisen emäksisyyden vaikutus hallitsee

myöhemmässä vaiheessa. Yksityiskohtainen rakenteellinen tutkimus AAM: ista, jotka on valmistettu Na-Mg-alumiinisilikaattilasista, osoittaa, että Mg AAM-yhdisteissä esiintyy amorfisena magnesiumsilikaatti (AMS) -faasina, jonka olemassaoloa ei ole hyvin dokumentoitu kirjallisuudessa. AMS: n muodostumisen liikkeellepaneva voima on Mg: n korkea CFS, mikä johtaa depolymeroitujen silikaattilajien tehokkaaseen vakautumiseen. Hydrotaltsiittiryhmän faasien puuttuminen näistä AAM: ista on havaittu johtuvan Al: n ehtymisestä zeoliittituotannolla. Flogopiittimineraalin arviointi Mg-rikkaana esiasteena alkalin aktivoitumiselle osoittaa, että käsittelemätön flogopiitti on erittäin inertti. Lämpökäsittely voi kuitenkin parantaa flogopiitin emäksistä reaktiivisuutta.

- **Utilization of peat-wood fly ash from fluidized bed combustion as supplementary cementitious material/ Rissanen, Jouni 2020**

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  Approximately 500 000 tons of non-coal fly ash are produced in Finland annually from energy generation sources, most of which is fluidized bed combustion fly ash (FBCFA) from the burning of peat and wood. This significant industrial side stream is not yet fully utilized, so that some is still escaping from the material circulation of circular economy. FBCFA is nevertheless a promising novel supplementary cementitious material, as it naturally possesses a fine particle size as well as suitable chemical and mineralogical composition properties. Utilization of this material would be beneficial for the environment, as it could potentially reduce the carbon footprint of concrete production and the environmental impacts of ash disposal. It would also be beneficial for ash producers, as it would provide a new route for reducing the amount of waste generated.

  The aim of this thesis was to study how FBCFAs originating from the co-combustion of peat and wood affect the properties of fresh and hardened mortars when used to replace 10–40% of the cement normally used in them, and also to examine the effect of FBCFAs on freeze-thaw durability.

  It was found that FBCFA acts as a beneficial reacting component in mortar rather than just an inert filler material. Its irregular particle shapes dramatically increase the water requirement of mortar, but it was found that with a sufficient dosage of superplasticizers it is possible to produce mortars with good workability even when 40% of the cement is replaced with FBCFA. In general, fluidized bed combustion fly ash slightly reduced the compressive strength of the mortar samples, but it clearly out-performed non-reactive filler materials and achieved roughly similar compressive strengths to those resulting from conventional coal fly ash. FBCFA increased the water requirement of fresh material due to irregular particle shape. However, sufficient dosage of superplasticizer enabled to prepare mortar with good workability. In addition, milling of FBCFA was found to be an effective method to

decrease the water requirement of fresh mortar. FBCFA increased the porosity, capillary water absorption and water vapour permeability of mortars, but unlike conventional coal fly ash it did not have any negative effect on the performance of the air entrainment agent nor on the freeze-thaw resistance of the mortars.

From a technical perspective, approximately 20% of the cement can be replaced with good quality FBCFA without significantly impairing the performance of the hardened material, although at the moment FBCFA does not conform to the European fly ash standard EN 450-1, which hampers its use. On the other hand, it could be still used in non-standardized applications. The future feasibility of FBCFA as a supplementary cementitious material is highly dependent on the legal incentives laid down and customers' attitudes towards sustainable construction materials.

Suomessa syntyy vuosittain noin 500 000 tonnia energiantuotannon lentotuhkia, jotka ovat peräisin muusta kuin kivihiilen poltosta. Suurin osa näistä tuhkista on peräisin puun ja turpeen leijupetipoltosta. Kaikkea syntyvää tuhkaa ei hyödynnetä vielä täysin ja osa tuhkista läjitetään kaatopaikoille. Leijupetipolton lentotuhka on kuitenkin lupaava sementin seosaine, sillä tuhkalla on luonnostaan hieno partikkelikoko ja sopiva kemiallinen koostumus. Tämän sivuvirran tuotteistaminen rakennusteollisuuden raaka-aineeksi olisi hyödyllistä ympäristön kannalta, sillä sen käyttö voisi pienentää sementin hiilijalanjälkeä sekä tuhkan läjittämisen ympäristövaikutuksia. Tämän lisäksi tuhkan hyödyntäminen sementin seosaineena hyödyttäsi tuhkan tuottajia, sillä tämä tarjoaisi uuden tavan vähentää syntyvän jätteen määrää.

Tämän työn tavoitteena on tutkia, miten puun ja turpeen yhteispoltosta syntyvä leijupetipolton lentotuhka vaikuttaa tuoreen ja lujittuneen laastin ominaisuuksiin, kun tuhkalla korvataan 10–40 % käytettävästä sementistä. Tämän lisäksi työssä tutkittiin leijupetipolton lentotuhkan vaikutusta laastin pakkasenkestävyyteen.

Työssä kävi ilmi, että leijupetipolton lentotuhka toimii laastissa reaktiivisena komponenttina, sen sijaan, että se olisi vain reagoimaton fillerimateriaali. Leijupetipolton lentotuhkan epäsäännöllinen partikkelimuoto nostaa merkittävästi laastin vedentarvetta, mutta riittävällä tehonotkistimen annostelulla voitiin valmistaa työstettävyydeltään hyviä laasteja, jopa silloin kun sementistä korvattiin 40 % leijupetipolton lentotuhkalla. Yleisesti ottaen leijupetipolton lentotuhkat heikensivät hiukan laastien puristuslujuutta. Lujuudet olivat kuitenkin huomattavasti parempia, kuin laasteissa, joissa vastaava määrä sementtiä korvattiin reagoimattomilla fillereillä, ja samaa tasoa kuin laasteissa, joissa sementti korvattiin perinteisellä hiilen pölypolton lentotuhkalla. Epäsäännöllisen partikkelimuodon vaikutuksesta tuhkat lisäsivät huomattavasti laastien vedentarvetta. Riittävällä notkistimen

annostuksella voitiin kuitenkin valmistaa laasteja, joiden työstettävyys oli hyvä. Myös tuhkan jauhatuksen todettiin olevan tehokas menetelmä työstettävyyden parantamiseksi. Leijupetipolton lentotuhka lisäsi laastien huokoisuutta, kapilaarista veden imeytymistä sekä vesihöyryn läpäisevyyttä. Leijupetipolton lentotuhkien todettiin soveltuvan myös pakkasenkestävän laastin valmistukseen, eikä tuhkilla ollut negatiivista vaikutusta huokostimen toimintaan.

Käytännössä noin 20 % sementistä voitaisiin korvata hyvälaatuisella leijupetipolton lentotuhkalla heikentämättä merkittävästi lujittuneen materiaalin ominaisuuksia. Tällä hetkellä eurooppalainen lentotuhka standardi EN 450-1 ei kata leijupetipolton lentotuhkaa, mikä rajoittaa sen käyttöä. Toisaalta, tuhka voitaisiin mahdollisesti hyödyntää sovelluksissa, joihin ei vaadita standardoitua betonia. Lähitulevaisuudessa leijupetipolton lentotuhkan hyödyntämisnäkymät ovat voimakkaasti riippuvaisia siitä, miten tuhkan hyödyntämistä rajoittava sääntely, sekä asiakkaiden suhtautuminen ympäristöystävällisiin rakennusmateriaaleihin kehittyvät.

- **Ettringite-based binder from ladle slag : from hydration to its fiber-reinforced composites/ Nguyen, Hoang 2020**

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  Ladle slag (LS) is a by-product of refining molten steel. Given that the production of one ton of crude steel produces 12–15 kg of LS, Europe produces approximately 2.6 million tons of this slag annually. In Finland, LS currently has limited use in low-value applications. It has shown high potential in producing cementitious binders due to its high calcium and aluminum content. The goal of this thesis is to offer the best solution to utilize LS in the construction industry for both its environmental and economic benefits. To achieve this goal, the present research focuses on two pathways:(1) Developing a cementitious binder with minimal pre-treatment for raw materials and chemicals that meets the requirements to be used as a construction material (papers I–II)(2) Producing a high-performance fiber-reinforced cementitious composite from the LS-based binder with a good balance of high mechanical performance, small carbon footprint, embodied energy, and high durability (papers II–IV).

  This thesis is based on studies that have found that LS can hydrate with gypsum to form an ettringite-based binder for which the only treatment needed is milling the precursors. Citric acid works effectively in the binder as a set retarder to control setting time and workability. The binder can thus be used in various construction applications. Polypropylene fiber can be used to produce the most balanced ettringite-based composite considering mechanical performance, CO_2 emission, and embodied energy with great resistance under chemical and physical stress.

The results of this thesis will enable better utilization of LS for high-value construction applications.

Mikserikuona (LS) on teräksenvalmistuksen sivutuote. Jokainen tonni raakaterästä voi tuottaa noin 12–15 kg kyseistä kuonaa, joten Euroopassa tuotetaan yhteensä noin 2,6 miljoonaa tonnia tätä kuonaa vuodessa. Suomessa LS:n käyttö on tällä hetkellä rajoittunut matalan lisäarvon sovelluksiin. Kyseinen kuona omaa kuitenkin suuren potentiaalin sementtisideaineiden valmistuksessa korkean kalsium- ja alumiinipitoisuutensa vuoksi. Tämän väitöskirjan tavoitteena on löytää korkeamman lisäarvon ratkaisu LS:n hyödyntämiseen rakennusteollisuudessa sekä ympäristön että taloudellisten hyötyjen näkökulmasta. Tämän tavoitteen saavuttamiseksi tässä tutkimuksessa tarkastellaan kahta hyödyntämisreittiä:(1) Rakennusmateriaalien mekaaniset vaatimukset täyttävän sementtisidosaineen kehittäminen minimaalisella raaka-aineiden esikäsittelyllä ja kemikaalien lisäyksellä (julkaisut I–II)(2) Korkean suorituskyvyn kuituvahvisteisen komposiitin kehittäminen LS-pohjaisesta sideaineesta, joka omaa korkean mekaanisen suorituskyvyn, pienen hiilijalanjäljen, korkean kestävyyden, ja jonka valmistus on energiatehokasta (julkaisut II–IV).

Tämä väitöskirja pohjautuu tutkimuksiin, joissa on todettu, että LS lujittuu yhteisreaktiossa kipsin kanssa muodostaen ettringiittipohjaisen sideaineen, jota varten ainoa tarvittava käsittely on raaka-aineiden jauhaminen. Sitruunahappo toimii sideaineessa tehokkaasti hidastimena säätäen asettamisaikaa ja parantaen työstettävyyttä. Sideainetta voidaan siten käyttää erilaisissa rakennussovelluksissa. Polypropeenikuituja voidaan käyttää tuottamaan optimaalinen ettringiittipohjainen komposiitti ottaen huomioon mekaaniset ominaisuudet, hiilidioksidipäästöt ja valmistusenergia, ja jolla on lisäksi riittävä kestävyys kemiallisessa ja fysikaalisessa rasituksessa. Tämän opinnäytetyön tulokset mahdollistavat LS:n paremman hyödyntämisen korkean lisäarvon sovelluksissa rakennusteollisuudessa.

- **A cementitious binder from high-alumina slag generated in the steelmaking process/ Adesanya, Elijah D. 2019**

  https://urn.fi/URN:ISBN:9789526224527

  About 4 Mt of ladle slag is generated in steelmaking processes in Europe per year, a large proportion of which (80%) is placed in landfills or stored. This pattern is expected to continue without further research for their valorisation due to increasing demand for quality steel products worldwide. Ladle slag (LS) produced in Finland possesses large amounts of calcium and aluminium and mineralogical phases which can exhibit cementitious capabilities and can be utilized in applications where expensive commercial cements are currently being used. The aim of this thesis is to investigate the properties of ladle slag in different activation pathways, including alkali activation and use as a hydraulic binder with gypsum.

The results showed that ladle slag can be used alone as a precursor in alkali activation or as the sole binder or a co-binder with gypsum in hydraulic binding. Depending on the activation pathway, compressive strength between 35–92 MPa can be achieved after 28 days. The reaction properties of alkali activated ladle slag are characterized, and it is confirmed through X-ray diffraction (XRD) that the reaction product after alkali activation is mainly an x-ray amorphous (calcium aluminate silicate hydrate-like) phase. Characterization techniques (SEM, XRD, TGA and NMR) used to analyze the LS paste binder with just water showed the hydration products of ladle slag to be dicalcium aluminate octahydrate (C_2AH_8), tricalcium aluminate hexahydrate (C_3AH_6), gibbsite (AH_3) and stratlingite (C_2ASH_8) was also identified after a prolonged period of hydration. Furthermore, it was found that to minimize the conversion, the ideal water-to-binder ratio is 0.35. The conversion mechanism is reduced at this ratio and the strength is slightly affected. Another pathway that can be used to annul the conversion of calcium aluminate hydrates formed in LS paste is through the addition of gypsum to the LS paste system to produce an ettringite-rich binder ($C_6A_3H_{32}$). When ettringite is formed in place of calcium aluminate hydrates the strength increases, frost resistance is improved, and drying shrinkage is enhanced.
Lastly, a potential application of ladle slag as a refractory material was also investigated.

Euroopassa syntyy vuosittain noin 4 Mt terästeollisuden sivutuotetta, JV-kuonaa, josta 80 % läjitetään tai kaatopaikoitetaan. Maailmanlaajuisesti syntyvän kuonan määrä tulee todennäköisesti kasvamaan laadukkaiden terästuotteiden ennustetun kysynnän kanssa. Tämän vuoksi kuonalle tulisi löytää hyötökäyttökohde, jota vältyttäisiin läjitykseltä. JV-kuona sisältääkin suuria määriä kalsiumia ja alumiinia sekä mineralogisia faaseja, joilla on sementtimäisiä ominaisuuksia. Näin kuonaa voitaisiin käyttää sovelluksissa, joissa tällä hetkellä käytetään kalliita kaupallisia sementtejä. Tämän väitöskirjan tarkoituksena oli tutkia JV-kuonan ominaisuuksia sementtimäisenä sideaineena alkali-aktivoinnissa sekä hydraulisena sideaineena yksinään että kipsin kanssa sekoitettuna.

Väitöskirjan tulokset osoittivat, että JV-kuonaa voidaan käyttää prekursorina alkali-aktivoinnissa tai hydraulisena sideaineena pelkästään veden kanssa tai yhdessä kipsin ja veden kanssa. Saavutetut puristuslujuuset vaihtelivat 35 ja 92 MPa:n välillä, jotka vastaavat normaalin ja erityislujan betonin lujuuksia. JV-kuonan reaktiotuotteet alkali-aktivonnin jälkeen analysoitiin XRD- ja FTIR-analyyseillä. Tuloksista nähtiin, että alkali-aktivoinnin jälkeen reaktiotuote on sementin kaltainen kalsium-aluminatti-silikaati-hydraati (C-A-S-H) -tyyppinen faasi. XRD-, SEM-, TGA- ja NMR-analyysit osoittivat JV-kuonan hydrataatiotuotteiden olevan erilaisia kalsium-aluminaattihydraatteja (C_2AH_8, C_3AH_6, AH_3 ja C_2ASH_8). Tämän vuoksi työssä tutkittiin eri vesi–kuona-suhteita, ja havaittiin, että kun käytetään alhaista

kuona-vesi -suhdetta (0,35), reaktiotuoteiden muutos vähenee ja lujuus paranee. Toinen tapa, jolla voidaan estää reaktiotuotteiden muuttuminen, on kipsin lisäys: lisäämällä kipsiä tuotetaan runsaasti ettringiittiä ($C_6A_3H_{32}$). Kun ettringiittiä muodostuu kalsium-aluminaattihydraattien sijaan, lujuus kasvaa, pakkaskestävyys paranee ja kuivumiskutistuma paranee.

Väitöskirjan viimeisessä osiossa tutkittiin JV-kuonan mahdollista käyttöä tulenkestävänä materiaalina ja huomattiin, että sen tulenkestävyysominaisuudet vaihtelevat käytetyn aktivointityypin mukaan.

- **Stabilization of sulphidic mine tailings by different treatment methods : heavy metals and sulphate immobilization/ Kiventerä, Jenni 2019**

  https://urn.fi/URN:ISBN:9789526223964

  Millions of tons of mine tailings are generated worldwide annually. Since many valuable metals such as Ag, Cu, Pb, Zn, Au and Ni are usually incorporated into sulphidic minerals, a large proportion of the tailings generated contain high amounts of sulphates and heavy metals. Some of these tailings are used as paste backfill material at mining sites, but large amounts are still being deposited into the tailings dams under water coverage. Sulphidic minerals are stable underground but after mining of the ore and several processing steps these minerals can be oxidized when they come into contact with water and air. This oxidation generates acid and thus reduces the pH of the surrounding environment. Furthermore, the heavy metals present in the mine tailings can be leached into the environment. This phenomenon, called Acid Mine Drainage (AMD), is one of the most critical environmental issues related to the management of sulphidic-rich tailings. Since AMD generation can still occur hundreds of years after closure of the mine, the mine tailings need stable, sustainable and economically viable management methods in order to prevent AMD production in the long term.

  The aim of this PhD thesis was to study various solidification/stabilization (S/S) methods for the immobilization of sulphidic mine tailings. The main focus was to develop a suitable chemical environment for achieving effective heavy metal (mainly arsenic) and sulphate immobilization while simultaneously ensuring good mechanical properties. Three treatment methods were tested: alkali activation, stabilization using hydrated lime ($Ca(OH)_2$) and blast furnace slag (GBFS), and calcium sulphoaluminate-belite (CSAB) cement stabilization.

  The mine tailings used in this study contained large amounts of sulphates and heavy metals such as Cr, Cu, Ni, Mn, Zn, V and As. The leaching of arsenic and sulphates from powdered tailings exceeded the legal limits for regular and inert waste. All treatment methods were found to generate a hardened matrix that was

suitable for use as a backfilling or construction material, but the calcium-based binding system was the most suitable for effective immobilization of all the heavy metals (including arsenic) and the sulphates. Precipitation in the form of calcium sulphates/calcium arsenate and the formation of ettringite are the main stabilization methods employed in calcium-based stabilization/solidification (S/S) systems. Some evidence of physical encapsulation occurring simultaneously with chemical stabilization was noted. These results can be exploited further to develop more sustainable mine tailing management systems for use in the future. The tailings could be stored in a dry landfill area instead of in tailing dams, and in this way a long-term decrease in AMD generation could be achieved, together with a high potential for recycling.

Monet arvometallit kuten kulta, kupari ja nikkeli ovat sitoutuneena sulfidipitoisiin mineraaleihin. Louhittaessa ja rikastettaessa näitä sulfidimineraaleja syntyy miljoonia tonneja sulfidipitoisia rikastushiekkoja vuosittain. Rikastushiekat voivat sisältää myös runsaasti erilaisia raskasmetalleja. Osa rikastushiekoista hyödynnetään kaivostäytössä, mutta suurin osa rikastushiekoista läjitetään edelleen ympäristöön rikastushiekka-altaisiin veden alle. Kun sulfidipitoinen malmi kaivetaan ja käsitellään, sulfidiset mineraalit hapettuvat ollessaan kosketuksissa veden ja hapen kanssa. Hapettuessaan ne muodostavat rikkihappoa, laskien ympäristön pH:ta jolloin useimmat raskasmetallit liukenevat ympäristöön. Muodostuvia happamia kaivosvesiä voi syntyä vielä pitkään kaivoksen sulkemisen jälkeen ja ovat näin ollen yksi suurimmista kaivosteollisuuteen liittyvistä ympäristöongelmista. Lisäksi suuret rikastushiekka-altaat voivat aiheuttaa vaaraa myös ihmisille, mikäli altaan rakenteet pettävät. Rikastushiekkojen kestäviä ja ympäristöystävällisiä varastointimenetelmiä täytyy kehittää, jotta näitä ongelmia voidaan tulevaisuudessa ehkäistä.

Tässä työssä tutkittiin menetelmiä, joilla kultakaivoksella syntyvät sulfidipitoiset vaaralliseksi jätteeksi luokitellut rikastushiekat saataisiin stabiloitua tehokkaasti. Työssä keskityttiin kolmeen erilaiseen menetelmään: alkali-aktivointiin, stabilointiin kalsiumhydroksidin ja masuunikuonan avulla ja stabilointiin CSAB sementin avulla. Valmistettujen materiaalien mekaanisia ja kemiallisia ominaisuuksia arvioitiin. Tavoitteena oli ymmärtää, miten eri menetelmät soveltuvat raskasmetallien (erityisesti arseenin) ja sulfaattien sitoutumiseen ja mikä on eri komponenttien rooli reaktioissa.

Alkali-aktivoimalla rikastushiekkaa sopivan sidosaineen kanssa saavutettiin hyvät mekaaniset ominaisuudet ja useimmat haitta-aineet sitoutuivat materiaaliin. Ongelmia aiheuttivat edelleen sulfaatit ja arseeni. Kalsiumpohjaiset menetelmät sitoivat raskasmetallit (myös arseenin) ja sulfaatit tehokkaimmin. Sulfaatit ja arseeni saostuivat muodostaen niukkaliukoisia komponentteja kalsiumin kanssa. Samanaikaisesti rakenteeseen muodostui ettringiittiä, jolla on tutkitusti hyvä kyky

sitoa erilaisia raskasmetalleja rakenteeseensa. Raskasmetallit myös kapseloituivat rakenteen sisään.

Työn tuloksia voidaan hyödyntää, kehitettäessä rikastushiekkojen turvallista varastointia. Kun materiaalille saavutetaan riittävän hyvä lujuus ja kemiallinen stabiilius, rikastushiekat voitaisiin läjittää tulevaisuudessa kuivalle maalle altaan sijaan. Näin vältyttäisiin rikastushiekka-altaiden rakentamiselta ja voitaisiin vähentää happamien kaivosvesien muodostumista pitkällä ajanjaksolla. Saavutettujen tulosten perusteella rikastushiekkoja voidaan mahdollisesti tulevaisuudessa hyödyntää myös erilaisissa betonin tapaisissa rakennusmateriaaleissa.

- **Alkali activation-granulation of fluidized bed combustion fly ashes/ Yliniemi, Juho 2017**

  https://urn.fi/URN:ISBN:9789526215624

  Biomass, such as wood, binds CO_2 as it grows, and is thus considered an environmentally friendly alternative fuel to replace coal. In Finland, biomass is typically co-combusted with peat, and also municipal waste is becoming more common as a fuel for power plants. Wood, peat and waste-based fuels are typically burned in fluidized bed combustion (FBC) boilers.

  Ash is the inorganic, incombustible residue resulting from combustion. The annual production of biomass and peat ash in Finland is 600 000 tonnes, and this amount is likely to increase in the future, since the use of coal for energy production will be discontinued during the 2020s. Unfortunately, FBC ash is still largely unutilized at the moment and is mainly dumped in landfills.

  The general aim of this thesis was to generate information which could potentially improve the utilization of FBC ash by alkali activation. The specific objective was to produce geopolymer aggregates by means of a simultaneous alkali activation-granulation process.

  It was shown that geopolymer aggregates with physical properties comparable to commercial lightweight expanded clay aggregates (LECAs) can be produced from FBC fly ash containing heavy metals. Although the ashes were largely unreactive and no new crystalline phases were formed by alkali activation, a new amorphous phase was observed in the XRD patterns, possibly representing micron-sized calcium aluminate silicate hydrate-type gels.

  The heavy metal immobilization efficiency of alkali activation varied with the type of fly ash. Good stabilization was generally obtained for cationic metals such as Ba, Pb and Zn, but in common with the results obtained with alkali activation of coal fly

ash, anionic metals became leachable after alkali activation. The efficiency of immobilization depended on the physical and chemical properties of the fly ash and was not related to the total content of the element.

All the geopolymer aggregates met the criteria for a *lightweight aggregate* (LWA) as defined by EN standard 13055-1. Their strength depended on the reactivity and particle size distribution of the fly ash. Mortars and concretes prepared with such geopolymer aggregates had higher mechanical strength, higher dynamic modulus of elasticity and higher density than concrete produced with commercial LECA, while exhibiting similar rheology and workability.

Biopolttoaineet, esimerkiksi puu, ovat ympäristöystävällinen vaihtoehto kivihiilelle, koska ne sitovat hiilidioksidia kasvaessaan. Suomessa biopolttoaineita poltetaan tyypillisesti turpeen kanssa, ja nykyään myös jätteen hyödyntäminen polttoaineena on yleistynyt. Puu, turve ja jätepolttoaineet poltetaan tyypillisesti leijupetipoltto-tekniikalla.

Tuhka on polton epäorgaaninen, palamaton jäännös. Puun ja turpeen tuhkaa tuotetaan Suomessa 600 000 tonnia vuodessa ja määrän odotetaan kasvavan, sillä kivihiilen poltto lopetetaan 2020-luvulla. Leijupetipolton tuhkaa ei tällä hetkellä juurikaan hyödynnetä ja tuhka päätyykin pääasiassa kaatopaikoille.

Tämän tutkielman päämääränä oli tuottaa tietoa, joka parantaisi leijupetipolton tuhkien hyödyntämistä alkali-aktivaatiolla. Erityisesti tavoitteena oli valmistaa geopolymeeriaggregaatteja yhtäaikaisella alkali-aktivaatiolla ja rakeistuksella.

Tutkielmassa osoitettiin, että raskasmetalleja sisältävistä tuhkista valmistettujen geopolymeeriaggregaattien fysikaaliset ominaisuudet ovat vertailukelpoiset kaupallisten kevytsora-aggregaattien (LECA) kanssa. Vaikka tuhkien reaktiivisuus oli matala, ja uusia kidefaaseja ei muodostunut alkaliaktivaatiolla, uusi amorfinen faasi havaittiin XRD-mittauksissa. Uusi amorfinen faasi oli mahdollisesti mikrometrikokoluokan kalsium-aluminaatti-silikaatti-hydraatti-tyyppinen rakenne. Raskasmetallien stabiloinnin tehokkuus vaihteli tuhkien välillä. Kationiset metallit, kuten barium, lyijy ja sinkki, stabiloituivat pääasiassa hyvin, mutta anionisten metallin liukoisuus kasvoi alkali-aktivoinnin myötä. Stabiloinnin tehokkuus riippui tuhkien fysikaalisista ja kemiallisista ominaisuuksista, mutta raskasmetallin kokonaispitoisuudella ei ollu vaikutusta.

Kaikki geopolymeeriaggregaatit olivat *kevytsora-aggregaatteja* standardin EN 13055-1 mukaisesti. Aggregaattien lujuus riippui tuhkan reaktiivisuudesta ja partikkelikokojakaumasta. Geopolymeeriaggregaateilla valmistettujen laastien ja betonien mekaaninen lujuus, Youngin moduuli ja tiheys olivat korkeampia kuin

kaupallisella kevytsora-aggregaateilla valmistetut, vaikka niiden reologia ja työstettävyys olivat samanlaisia.

3. VTT

Vähähiilisten betonien säilyvyysmitoitus (Tampereen yliopiston ja TAMKin kanssa), 2025

https://research.tuni.fi/betonirakenteet/tutkimus/tutkimuskokonaisuudet/vahahiilisten-betonien-sailyvyysmitoitus/

Hankkeessa tutkittiin vähähiilisten betonien pitkäaikaiskestävyyttä ja niiden kytkemistä uuden Eurokoodin (SFS-EN 1992-1-1:2023) mukaiseen suorituskykyperusteiseen säilyvyysluokitukseen (ERC). Tavoitteena oli määrittää vähähiilisiä sideaineita sisältäville betoneille niiden todelliseen suorituskykyyn perustuvat raudoitteiden peitepaksuudet eri rasitusolosuhteissa ja edistää näin vähähiilisten ratkaisujen käyttöä rakennesuunnittelussa.

Hanke toteutettiin Tampereen yliopiston, VTT:n ja TAMK:n yhteistyönä, ja siinä valmistettiin neljää sideainetta käyttäen 48 betonia, yli 1000 koekappaletta ja tehtiin yli 10 000 mittausta. Tutkimus sisälsi kiihdytettyjä karbonatisoitumis- ja kloridikokeita, halkeamien vaikutusten arviointia sekä pitkäaikaiskenttäkappaleiden valmistuksen. Laskennallisessa osuudessa mallinnettiin peitepaksuudet kaikille tutkituille betoneille sekä säilyvyysluokille suomalaisissa olosuhteissa.

Tulokset osoittivat, että vähähiiliset, masuunikuonapitoiset sideaineet paransivat kloridinkestävyyttä merkittävästi. Sen sijaan karbonatisoituminen lisääntyi sementin korvausasteen ja vesi-sideainesuhteen kasvaessa. Halkeamien todettiin lisäävän sekä hiilidioksidin että kloridien etenemistä, mikä korostaa halkeilun hallintaa.

Hankkeen tulokset ovat välittömästi hyödynnettävissä. Tuloksia hyödynnetään käynnissä olevassa standardointityössä ja ne vaikuttavat alan käytäntöihin uusien Eurokoodien käyttöönoton myötä. Lisäksi hankkeessa validoidut koemenetelmät ja koottu tietokanta tukevat uusien vähähiilisten sideaineiden kehitystä ja yhdenmukaista arviointia jatkossa.

Hankkeella on merkittävä positiivinen vaikutus rakentamisen vähähiilisyyteen, sillä se mahdollistaa turvallisen siirtymän vähäpäästöisempiin betoniratkaisuihin ilman säilyvyyden heikentymistä. Jatkotutkimustarpeiksi tunnistettiin erityisesti kenttäkoekappaleiden pitkäaikaisseuranta, kiihdytettyjen ja luonnollisten rasitusolosuhteiden vertailu sekä Suomen olosuhteita kuvaavan tarkemman ilmasto- ja materiaalidatan kerääminen.

Durability design of low-carbon concrete

The project investigated the long-term durability of low-carbon concretes and their connection to the performance-based durability classification (ERC) according to the new Eurocode (SFS-EN 1992-1-1:2023). The aim was to determine the actual performance-based reinforcement cover thicknesses for concretes containing low-carbon binders under different load conditions and thus promote the use of low-carbon solutions in structural design.

The project was carried out in cooperation between the University of Tampere, VTT and TAMK, and 48 concretes, over 1000 test specimens and over 10,000 measurements were made using four binders. The study included accelerated carbonation and chloride tests, assessment of the effects of cracks and the preparation of long-term field specimens. The computational part modelled the cover thicknesses for all tested concretes and durability classes in Finnish conditions.

The results showed that low-carbon, blast furnace slag-containing binders significantly improved chloride resistance. On the other hand, carbonation increased with increasing cement replacement and water-binder ratio. Cracks were found to increase the propagation of both carbon dioxide and chlorides, which emphasizes crack control.

The results of the project can be utilized immediately. The results will be utilized in the ongoing standardization work and will influence industry practices with the introduction of new Eurocodes. In addition, the test methods validated in the project and the compiled database will support the development and uniform assessment of new low-carbon binders in the future.

The project will have a significant positive impact on low-carbon construction, as it enables a safe transition to lower-emission concrete solutions without compromising durability. The identified needs for further research include, in particular, long-term monitoring of field test specimens, comparison of accelerated and natural stress conditions, and the collection of more accurate climate and material data describing Finnish conditions.

Low-CO_2 Ferrite-rich Belite Ye'elimite Cements/Rahul Roy

https://lirias.kuleuven.be/4241325?&lang=en

Roy, Rahul, et al. "Beyond Bauxite or Alumina: A Review of Alternative Alumina Rich Sources for Calcium-Sulfo Aluminate Cement Production." Nordic Concrete Research, vol. 73, no. 2, Nordic Concrete Federation, 2025, pp. 41-55. https://doi.org/10.2478/ncr-2025-0016.

Roy R., Hertel T., Rößler C., Pontikes Y. “Exploring the Hydration Potential and Kinetics of Na-Ye'elimite and Ti-Ferrite Solid Solutions in Iron-Rich CSA “, (2026) Cement and Concrete Research. https://doi.org/10.1016/j.cemconres.2025.108046

Roy R., Hertel T., Pontikes Y.” Influence of citric acid and triisopropanolamine on reactivity, hydration, and mortar assessment of Valoxy containing Fe-rich CSA-gypsum/anhydrite blends”, (2024) Construction and Building Materials https://doi.org/10.1016/j.conbuildmat.2025.142434

This PhD dissertation focuses on developing an environmentally friendly alternative to traditional Portland cement, which is a major source of global CO_2 emissions, responsible for 7% of the CO_2 emissions worldwide in 2024. The study explores a new type of cement called ferrite-containing belite-ye’elimite sulfoaluminate cement, which can significantly reduce both carbon emissions and energy use during production. A key innovation of this work is the use of industrial by-products—mainly bauxite residue and salt slag—to replace the expensive and limited raw materials such as bauxite, typically used to make calcium sulfoaluminate (CSA) cement. These residues, rich in alumina and iron, allow for the production of CSA cement at lower temperatures and with improved environmental and economic performance. In these synthesized cements, over 35% of the raw materials in the cement come from bauxite residue, and alumina-rich salt-slag was successfully used to completely replace bauxite, increasing the strength-giving phases in the cement. This approach supports a circular economy by turning industrial waste into valuable resources while potentially creating synergies between the aluminum and cement industries. However, challenges remain. One key issue is that the iron-rich components in the cement (called ferrites) do not react quickly enough with water, which can reduce performance. The research investigates ways to improve this, such as adding sulfate minerals and chemical additives like triisopropanolamine (TIPA). The results show that finding the right balance of these additives is crucial to enhance early strength and overall performance.

Overall, this work demonstrates a promising route toward more sustainable and circular cement production by combining waste valorization, process innovation, and chemical optimization.

Vähähiilidioksidipitoiset ferriittipitoiset Belite Ye’elimite -sementit

Tämä väitöskirja keskittyy ympäristöystävällisen vaihtoehdon kehittämiseen perinteiselle portlandsementille, joka on merkittävä maailmanlaajuisten hiilidioksidipäästöjen lähde ja vastaa 7 prosentista maailmanlaajuisista hiilidioksidipäästöistä vuonna 2024. Tutkimuksessa tutkitaan uudenlaista sementtiä, ferriittiä sisältävää beliitti-ye’elimiittisulfoaluminaattisementtiä, joka voi merkittävästi vähentää sekä hiilidioksidipäästöjä että energiankulutusta tuotannon aikana. Työn keskeinen innovaatio on teollisuuden sivutuotteiden – pääasiassa

bauksiittijäännöksen ja suolakuonan – käyttö kalliiden ja rajallisten raaka-aineiden, kuten bauksiitin, korvaamiseksi. Bauksiittia käytetään tyypillisesti kalsiumsulfoaluminaattisementin (CSA) valmistuksessa. Nämä alumiinioksidi- ja rautapitoiset jäännökset mahdollistavat CSA-sementin tuotannon alhaisemmissa lämpötiloissa ja paremmalla ympäristö- ja taloudellisella suorituskyvyllä. Näissä syntetisoiduissa sementeissä yli 35 % sementin raaka-aineista on peräisin bauksiittijäännöksestä, ja alumiinioksidipitoista suolakuonaa käytettiin onnistuneesti bauksiittia korvaamaan kokonaan, mikä lisäsi sementin lujuutta antavien faasien määrää. Tämä lähestymistapa tukee kiertotaloutta muuttamalla teollisuusjätteen arvokkaiksi resursseiksi ja samalla luomalla synergioita alumiini- ja sementtiteollisuuden välille. Haasteita on kuitenkin edelleen. Yksi keskeinen ongelma on, että sementin rautapitoiset komponentit (ns. ferriitit) eivät reagoi riittävän nopeasti veden kanssa, mikä voi heikentää suorituskykyä. Tutkimuksessa selvitetään tapoja parantaa tätä, kuten sulfaattimineraalien ja kemiallisten lisäaineiden, kuten tri-isopropanolamiinin (TIPA), lisäämistä. Tulokset osoittavat, että näiden lisäaineiden oikean tasapainon löytäminen on ratkaisevan tärkeää alkulujuuden ja kokonaissuorituskyvyn parantamiseksi.

Kaiken kaikkiaan tämä työ osoittaa lupaavan reitin kohti kestävämpää ja kiertotalouteen perustuvaa sementintuotantoa yhdistämällä jätteen hyödyntämisen, prosessi-innovaatiot ja kemikaalien optimoinnin.

FFS2 (Towards fossil-free steel phase 2)

Oey, T., et al. (2026) “Performance evaluation of slag-cement blends utilizing novel electric arc furnace slag” (in preparation for submission to Construction and Building Materials)

Transforming the steel process into a fossil-free one is a multi-technological challenge, and new expertise is being created widely, from managing the actual process to managing side streams. The FFS2 consortium comprises ten companies and three research institutions – the University of Oulu, VTT Technical Research Centre of Finland and Åbo Akademi University. The project is being funded by Business Finland and coordinated by environmental consultant Macon Oy.

The side streams (slag, dust) generated in fossil-free steel production are different in composition from the traditional blast furnace-based process, as was noted in the previous FFS1 project. The utilization of these new side stream products requires research so that they can be utilized effectively in, for example, the cement industry to produce blended cements with EAF slag.

FFS2 (Kohti fossiilivapaata terästä, vaihe 2)

Teräsprosessin muuttaminen fossiilivapaaksi on monialainen haaste, ja uutta osaamista syntyy laajasti itse prosessin hallinnasta sivuvirtojen hallintaan. FFS2-konsortioon kuuluu kymmenen yritystä ja kolme tutkimuslaitosta – Oulun yliopisto, VTT ja Åbo Akademi. Hanketta rahoittaa Business Finland ja sitä koordinoi ympäristökonsultti Macon Oy.

Fossiilivapaassa teräksen tuotannossa syntyvät sivuvirrat (kuona, pöly) ovat koostumukseltaan erilaisia kuin perinteisessä masuunipohjaisessa prosessissa, kuten edellisessä FFS1-hankkeessa todettiin. Näiden uusien sivuvirtatuotteiden hyödyntäminen vaatii tutkimusta, jotta niitä voidaan hyödyntää tehokkaasti esimerkiksi sementtiteollisuudessa valokaariuunikuonaa sisältävien seosten valmistuksessa.

EURAD2 (European partnership on radioactive waste management)

"Compatibility of Untreated Spent Ion-Exchange Resins in Alkali-Activated Metakaolin-based Binders as Light-Weight Aggregates: Dimensional Stability and Microstructural Characterization" (submitted abstract for International Congress on the Chemistry of Cement (ICCC 2027)

EURAD-2 builds upon EURAD and PREDIS to further implement a joint strategic programme of research & development, strategic studies and knowledge management activities at the European level, bringing together and complementing EU Member States' programmes in order to ensure cutting edge knowledge creation and preservation in view of delivering safe, responsible and publicly acceptable solutions for the management of radioactive waste throughout all programme phases (from "cradle to grave") across Europe now and in the future.

Spent ion exchange resins (IER) represent a challenging waste stream due to their tendency to absorb water and associated volume changes when incorporated into cementitious matrices. This work explores the feasibility of incorporating spent IER as a partial replacement for fine aggregates in metakaolin-based alkali-activated mortars (AAMs), while controlling swelling through activator chemistry.

EURAD2 (eurooppalainen kumppanuus radioaktiivisen jätteen käsittelyssä)

EURAD-2 pohjautuu EURAD:iin ja PREDIS:iin toteuttaakseen edelleen yhteistä strategista tutkimus- ja kehitysohjelmaa, strategisia tutkimuksia ja tiedonhallintatoimia Euroopan tasolla. Ohjelma kokoaa yhteen ja täydentää EU:n jäsenvaltioiden ohjelmia varmistaakseen huippuluokan tiedon luomisen ja säilyttämisen, jotta voidaan tarjota turvallisia, vastuullisia ja julkisesti hyväksyttäviä ratkaisuja radioaktiivisen jätteen käsittelyyn kaikissa ohjelman vaiheissa ("kehdosta hautaan") kaikkialla Euroopassa nyt ja tulevaisuudessa.

Käytetyt ioninvaihtohartsit (IER) edustavat haastavaa jätevirtaa, koska niillä on taipumus imeä vettä ja tähän liittyy tilavuuden muutoksia, kun niitä lisätään sementtipohjaisiin matriiseihin. Tässä työssä tutkitaan, voidaanko käytettyjä ioninvaihtohartseja käyttää osittain korvaamaan hienoja kiviaineksia metakaoliinipohjaisissa alkaliaktivoiduissa laasteissa (AAM), samalla kun turpoamista hallitaan aktivaattorikemian avulla.