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Exploring the use of fine surplus silica sand in low CO_2 emission earth construction

Exploration de l'utilisation de sable de silice excédentaire fin dans la construction terrestre à faible émission de CO_2

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ABSTRACT: The usage of industries' by-products and recycled materials in construction has become crucial for a sustainable future, as it reduces waste, has economic benefits, and helps to preserve natural resources while lowering CO_2 emissions. This research explored the possibility of utilizing fine silica sand, a by-product of quarrying, as a construction material aligned with circular economy strategies. Investigating various by-products alongside surplus fine silica sand from Nilsiä district, Finland, the study aimed to identify optimal recipes for stabilized silica sand blocks. The main focus was on experimentally assessing the technical properties of these blocks and evaluating the suitability of silica sand for sustainable rammed earth construction techniques. The filler and aggregates used were silica sand as well as quarry fines, while the binders included bio-based fly ash, bottom ash, green liquor dreg, lime kiln dust and cement. The material's index properties were measured, and the binders were tested for the flexural and compressive strength. Selected binders, exhibiting strength properties, were incorporated with sand and quarry fines to prepare cylindrical blocks, subsequently subjected to uniaxial compression tests. The comparison of 28 days cured compressive strength of different recipes revealed that samples containing bio-based fly ash with ratios of 1:5 and 1:6 binder to aggregate demonstrated superior results, with the best recipe containing a 50%-50% ratio of quarry fines to sand and a binder to aggregate ratio of 1:6, containing fly ash sourced from paper and pulp industry.

RÉSUMÉ: L'utilisation des sous-produits industriels et des matériaux recyclés dans la construction est devenue cruciale pour un avenir durable, car elle réduit les déchets, offre des avantages économiques et aide à préserver les ressources naturelles tout en réduisant les émissions de CO2. Cette recherche a exploré la possibilité d'utiliser du sable de silice fine, un sous-produit de l'exploitation de carrières, comme matériau de construction aligné sur les stratégies d'économie circulaire. En étudiant divers sous-produits aux côtés du surplus de sable de silice fine du district de Nilsiä, en Finlande, l'étude visait à identifier des recettes optimales pour des blocs de sable de silice stabilisés. L'accent principal a été mis sur l'évaluation expérimentale des propriétés techniques de ces blocs et sur l'évaluation de la pertinence du sable de silice pour les techniques de construction en terre battue durables. Les charges et agrégats utilisés étaient du sable de silice ainsi que des résidus de carrière, tandis que les liants comprenaient des cendres volantes biologiques, des cendres de fond, des résidus de liqueur verte, de la poussière de four à chaux et du ciment. Les propriétés index du matériau ont été mesurées et les liants ont été testés pour leur résistance à la flexion et à la compression. Des liants sélectionnés, présentant des propriétés de résistance, ont été incorporés avec du sable et des résidus de carrière pour préparer des blocs cylindriques, ensuite soumis à des tests de compression uniaxiale. La comparaison de la résistance à la compression des différentes recettes durant une période de 28 jours de durcissement a révélé que les échantillons contenant des cendres volantes biologiques avec des ratios de liant à agrégat de 1:5 et 1:6 ont montré des résultats supérieurs, avec la meilleure recette contenant un ratio de 50%-50% de résidus de carrière à du sable et un ratio de liant à agrégat de 1:6, contenant des cendres volantes provenant de l'industrie du papier et de la pâte.

Keywords: Sustainable construction; low CO_2 binders; circular economy; silica sand; quarry fine.

1 INTRODUCTION

Within the last decade, due to the increased environmental and economic benefit, re-use of recycled glass as the source material in glass and China production is adapted in many European countries. Due to this, the demand for fine-grained (< 1 mm) silica sand has decreased, and it is resulted in a problem in mass balance and surplus of the material on many quartzite quarry sites. Additionally, transporting large quantities of this material to regions with higher demand is deemed unsustainable.

In addition, with the rise of awareness about circular economy, it is essential to acquire by-products from mining, forestry, and energy industries in a manner that is consistent with the trend.

This study tries to evaluate the usage possibility of fine sand together with other secondary materials in non-load-bearing structure construction. This may provide a sustainable solution for the surplus of the material, assist with the waste management, and foster a more environmentally responsible approach to building practices.

One of the methods of construction that employs the use of secondary materials is rammed earth technology. In this method of construction, a damp material composed of soil, sand, silt or clay is rammed into a formwork. After the material has achieved the desired height the formwork is removed revealing a monolithic wall structure. In modern construction, besides the artistic reasons, the primary objective of utilizing rammed earth is to enhance its strength properties to meet the standards' requirements. To achieve this, stabilized rammed earth compositions typically integrate a small proportion of cement, typically ranging from 5% to 10% (Avila et al., 2022). In the stabilized rammed earth technique, the binder interacts with the available water, initiating a hydraulic binding process that contributes to the structural cohesion of the material (Jaquin, 2012). Numerous studies on the rammed earth technique highlight the influence of water content on the final strength of the structure. Unconfined compressive strength (UCS) achieved through the rammed earth technique typically span from 0,5 to 4 MPa, while the stabilized rammed earth technique can attain strengths exceeding 10 MPa after 7 days of curing. The strength ranges can vary depending on the type of aggregates and binders and the amount of water used. Nevertheless, the process of hydration and strength gain is gradual in these types of structures, therefore, the immediately post-construction strength measurements may not provide a realistic result (Jaquin et al., 2009; Walker et al., 2005).

In an experimental study, Holopainen (2022) investigated the possibility of using the recycled materials generated in Helsinki metropolitan area in rammed earth technology by constructing a testing-scale wall. In their work they studied the compressive strength of blocks made of different recipes of fly ash, crushed concrete, slag, and excavated desulphurization products with small amounts of cement. The compressive strength of his laboratory samples varied between 0,43-11,85 MPa, and it was concluded that the variation of the test results was an indicator of the susceptibility of the method to errors in the construction work. The main factors affecting the final results were named as: thoroughness of material mixing, initial moisture content of the mixture, and the compaction method.

Limited research exists on the properties of quarry fines in relation to rammed earth technology. However, Zhang et al. (2019) investigated the mechanical properties of stabilized quarry fines to be used in base and subbase layers in pavement construction. The quarry fines size ranging 0 to 4 mm were stabilized with cement, Ecolan Infra 80 (composed of coal ash, wood biomass, lime, and 20% cement) and fly ash from 100 % coal combustion residuals. Their cement stabilized samples showed acceptable performance for base layer applications when compacted to at least 93% of its maximum dry density.

The use of clean, fine quarried silica sand, characterized by angular-shaped grains, in conjunction with recycled material has not yet been explored in existing literature. However, the use of foundry sand, primarily consisting of uniformly sized, round-grained silica sand, has been studied in a few previous works. Zhang et al. (2021) have studied the use of stabilized waste foundry sand, (WFS) for applications in pavement structures. After monitoring the strength and durability properties of the proposed mixtures, they concluded that stabilized waste foundry sand (WFS) in combination with crushed rock exhibits promising potential for utilization in pavement structural layers. Malathy et al., (2022) tried to address the depletion of natural aggregates, by investigating the use of industrial silica sand as a substitute for natural fine aggregates in concrete. In their study it was concluded that all silica sand samples perform lower strength when compared to reference river sand and manufactured sand, and that the workability of concrete substituted with silica sand is superior to the concrete samples containing river sand.

In the current research, the silica sand from Nilsiä district of Finland was tested together with quarry fines as the main frame of the mixtures for the testing program. The by-products of a close-by forestry (paper and pulp) industry, namely bio-based fly ash, bottom ash, lime kiln dust and green liquor dreg together with by-products of a local energy company, namely: bio-based fly ash and bottom ash, was used as possible binders together with small amounts of cement as activator, to prepare samples. The aim of the research is to explore the potential application of different low carbon embedded recipes within the construction industry, in alignment with circular economy principles, as well as to determine the suitable ratios for the silica sand-containing mixtures adapted for different construction needs including non-load-bearing structures and noise barrier walls.

2 MATERIALS AND METHODS

The sand sample used in the study was a uniform poorly graded silica sand obtained from SIBELCO company's quarrying operation in Nilsiä located in Northern Savonia region of Finland. The fine fraction of silica sand (0.1 to 0.6 mm) is of less demand in the industry and is recently considered as a side stream product in quartzite quarrying activities.

As the coarser portion of the mixtures, quarry fines were used. The quarry fines (QF) are secondary product of the rock crushing process, characterized by a high fine grain size content. The quarry fines used in this study had a grain size distribution of 0 to 8 mm and the geological composition of the source rock was identified as Quartz syenite.

The material used for main frame of the mixtures, sand and QF, was dried for 24 hours at at the oven of 110 ± 5 °C. Subsequently, quartering was performed to prepare the samples for their index properties testing. Specific gravity and sieve analysis tests were performed according to SFS-EN ISO 17892-3 and SFS-EN 933-1, respectively. The maximum dry density (MDD) and optimum moisture content (OMC) of the material were then determined according to SFS-EN 13286-2 standard by using modified Proctor test. The Index properties of the material can be found in Table 1.

Table 1. Index properties.

Property	Silica sand	Quarry fine
Specific gravity	2,65	2,72
Percent fine <0,063 mm, (%)	0,1	6,15
C_u	2,5	0,9
D_{50}, (mm)	0.6	0,9
OMC, (%)	10	10,5
MDD, (g/cm^3)	1,57	2,15

To explore potential sustainable binder materials, an initial investigation was undertaken to identify locally sourced by-products. The aim was to minimize the requirement for long-distance transportation, thereby lowering CO_2 emissions. Stora Enso Oy, a provider in the renewable bio-products industry operating within the same region, supplied this work with five types of by-products: bio-based fly ash (1), two variants of bottom ash (1 & 2), lime kiln dust (LKD), and green liquor dreg. Additionally, Savon Voima, a local energy company, provided two of their own by-products: bio-based fly ash (2) and bottom ash (3). To assess the binding properties of these products in the presence of an activator, the flexural and compressive strengths of the hardened mortars, were tested after curing for 28 days, following the European standard SFS-EN 196-1:2016. Following the methodology outlined by Holopainen (2022), the proportion of activating agent, CEM I, was set up at 20%, while the remaining 80% was allocated to various binders. The test results of the strength properties of activator added binders are provided in table 2. The green liquor dreg did not exhibit any hardening properties, attributable to its high initial water content. Consequently, it was excluded from the designed recipes.

Table 2. Strength of activated binders.

Specimen	Flexural strength (MPa)	Compressive strength (MPa)
Fly ash 1 + CEM I	2,5	7,5
Bottom ash 1 + CEM I	1,5	4,5
Lime kiln dust + CEM I	0,4	0,9
Fly ash 2 + CEM I	1,6	5,8
Bottom ash 2 + CEM I	4,4	23,1
Green liquor dreg+ CEM I	NA	NA
Bottom ash 3 + CEM I	3,2	10,1

3 RESULTS AND DISCUSSIONS

The initial combination utilized in this study, referred to as Recipe-1, contain 75% quarry fines and 25% silica sand serving as the frame material together with binders. The binders were added at ratios of 1:5 and 1:6 binder to aggregate, respectively, to develop potential working recipes.

For evaluating the compressive strength following a 7-day curing period, a total of twelve specimens were prepared using an intensive compactor tester (ICT) machine. As shown in Figure 1, the stabilized mixture containing Fly ash 1, from Stora Enso, showed the highest recorded strength of 6,85 MPa. This fly ash was collected from a bed boiler that has a 150 MW thermal output and operates at an efficiency of 88%, with the annual production output of 5000 metric tons fly ash. Wood-based fuels such as bark, wood chips, forest chips and wood residue classes A and B, which are obtained from the factory and external sawmills are used as the main fuel type for this boiler. In addition, peat and sewage treatment plant sludge can be burned and coal is used as back-up fuel. The elevated chloride content present in this fly ash could be attributed to its higher strength, as chlorides are recognized accelerators of compressive strength in mortars and concrete. Fly ash 1, in particular, contains chloride, different oxides, and sulphate ions. The presence of chloride ions within the hydrated cement pore water stimulates the activator's hydration, thereby enhancing the strength gain (Galan and Glasser, 2015). Similarly, at a ratio of 1:5, the mixture containing fly ash 2 exhibited promising results, likely due to the same mechanism. Conversely, to the fly ash bearing samples, the remaining four binders exhibited less favourable outcome for the 1:5 and 1:6 binder-aggregate ratios. Consequently, a higher binder content was deemed necessary for these recipes, prompting an adjustment to binder-aggregate ratio to 1:3.

The percentage increase in strength, comparing the 1:5 to 1:3 ratios of binder to aggregates, were 25%, 77%, 132%, and 4% for samples containing bottom ash 1, lime kiln dust, bottom ash 2, and bottom ash 3, respectively as visible in Figure 1.

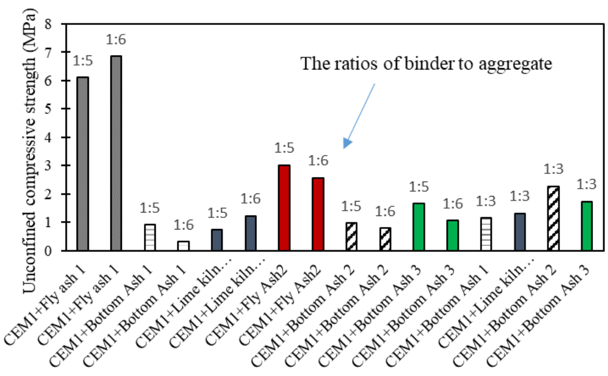

Figure 1. Unconfined compressive strength of 7-day.

Based on the revised recipes, the four best-performing binders exhibiting strengths were selected along with their corresponding ratios. Three specimens were prepared for each recipe to undergo testing for 28-day cured compressive strength. On the other hand, in order to maximize the utilization of the fine side stream sand, Recipe-2 was introduced, which involved a reduction in the amount of quarry fines by 25%, while maintaining the same ratios of binders. Following changing the ratio of quarry fines to sands to 50-50% the 7 days strength of samples were measured, and the comparison of result can be seen in figure 2. It is evident that the impact of this change varies across different recipes. For samples containing lime kiln dust, the frame material ratio change led to a notable 65% enhancement in strength compared to Recipe-1. However, in the remaining samples, it resulted in a strength reduction ranging from 26% to 117%.

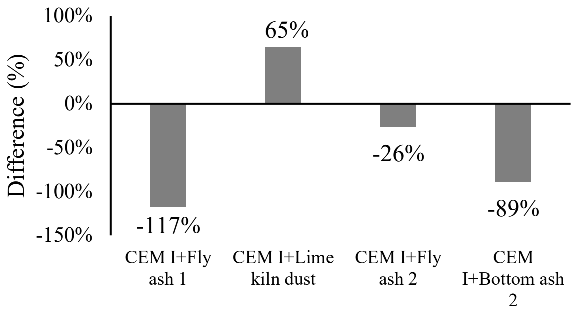

Figure 2. Comparison of 7-day strength difference from 75-25% (recipe 1) to 50-50% quarry fine-sand (recipe 2).

Among the recipes yielding better results in Recipe-2, those containing fly ash 1 and lime kiln dust (LKD) demonstrated strengths of 3.15 MPa and 3.17 MPa, respectively. These two samples were selected for comparison of their 28-day compressive strengths. Table 3 displays the results for both 7-day and 28-day compressive strengths of the selected samples of Recipe-1 and Recipe-2. These samples were prepared by ramming technique in five layers with a 4 kg hammer dropped 20 times from 0.45meter height. It can be observed that all samples, except those containing lime kiln dust, demonstrated strength gain with the extension of curing time.

Previously, it has been noted that incorporating lime kiln dust (LKD) into ash-bearing concrete mixtures and mortars leads to an increase in their water demand (Dvorkin and Zhitkovsky, 2023). This phenomenon suggests that LKD retains a higher water absorption capacity compared to CEM I, potentially attributed to its porous and larger particle size (Latif et al., 2015). In stabilized samples prepared using the rammed earth technique, compaction occurs at a relatively low water content. Consequently, the rapid absorption of available water by LKD can impede the hydration process of the remaining calcite (both from the activator and binder) in the mixture. This can lead to a cessation or even reversal of the strength gain process.

Table 3. Compressive strength of the final recipes.>

Quarry fine to sand ratio	Binder	Binder to aggregate	7 days strength (Mpa)	28 days strength (Mpa)
75%-25%	CEM I+Fly ash 1	1:6	3,15	4,83
75%-25%	CEM I+Fly ash 2	1:5	2,39	4,89
75%-25%	CEM I +Bottom ash 2	1:3	1,2	3,17
75%-25%	CEM I+Lime kiln dust	1:3	3,73	3,67
50%-50%	CEM I+Fly ash 1	1:6	3,15	6,61
50%-50%	CEM I+Lime kiln dust	1:3	3,73	2,56

4 CONCLUSIONS

The suitability of utilizing by-products of fine silica sand and quarry fines as construction materials was evaluated through a comparative study, with a particular focus on the compressive strength properties. Six different types of low CO_2 binders were employed to produce stabilized mixtures. Two ratios of 25% to 75 % and 50% to 50% of quarry fines to sand were kept as the base for frame material, while the proposed binders were added at 1:6, 1:5 and 1:3 ratios of binder to aggregate. Overall, samples containing bio-based fly ash in different mixtures and recipes demonstrated superior results, with the best recipe containing 50%-50% quarry fines to sand ratio, containing the bio-based fly ash from paper and pulp industry. It can be concluded that the higher concentration of fine silica sand particles in the mixture resulted in a wider range of gradation distribution of material within the standard upper and lower limits of aggregates. This, in turn, leads to a tighter packing of materials, particularly when combined with quarry sand and fly ash. Consequently, the reduction in void space within the material contributes to an increase in compressive strength. Additionally, it was observed that the effect of curing time on lime kiln dust containing samples was slightly detrimental. Further research is still required to assess the durability of utilized recipes over the long term and to enhance their strength properties.

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