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ARTICLE

Reutilization Potential of Fine Fraction from Construction and Demolition Waste in the Circular Economy

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ABSTRACT

Fine fraction waste is a remarkable secondary material without a rational utilization objective, demonstrating a real research gap for its study. The fine fraction can constitute up to several dozen percent of the total waste volume, representing a significant amount of material, but the nature of material can be partly complex and heterogeneous, restricting its utilization. Therefore, this study investigated the availability of fine fraction waste and its physical features, such as particle size, shape, and elemental composition. The fine fraction constituted 20–40% of construction and demolition waste and 25% of mechanical treatment of the waste, with particle sizes ranging from 0–15 mm. The novelty results from the study showed that the choice of treatment method could modify the particle size distribution and aspect ratio, and that no significant concentrations of harmful substances were found. Various scenarios of fine fraction availability were created, indicating its potential as a raw material in low-population areas. Because rational solutions for the fine fraction are lacking, novel innovations are needed for societies to take steps to approach the targets for a circular economy. This study shows that new approaches have the potential to enable the use of fine fraction waste as a partial replacement for other materials, for example, the use of fine fraction as a substitute for cementitious materials that can decrease emissions remarkably.

Keywords: Circular Economy; Construction and Demolition Waste (CDW); Fine Fraction; Separation

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1. Introduction

1.1. Construction and Demolition Waste (CDW) Recycling

Rational utilization of raw materials is an important topic in the modern economy, and sustainable waste management plays a key role in its effectiveness. A remarkable category in the waste management sector is construction and demolition waste (CDW), which accounts for 30–40% of total solid waste globally [1]. The CDW percentage of total waste volume varies significantly among various regions. For example, in the European Union, 36% of the total waste from all economic activities and households is generated by the construction sector [2], but the corresponding rate is close to 67% in the United States [3]. For reutilization purposes, the recovery of CDW is important, and in the EU, recovery rates have been in great turmoil during the past decade [2, 4]. Developed economies have a significant effect on CDW generation because the three largest economies (China, the United States (US), and the EU) are the top three CDW generators [5]. However, the above-presented CDW data represents information from developed areas without information from developing countries, where CDW management practices might be ineffective; thus, there is an emerging need for wider information on CDW management. Worldwide urbanization is a good indicator of the growing CDW percentage [4].

The socio-economic advantages of CDW utilization have been recognized as remarkable. For example, the study of Dahlbo et al. [6] demonstrated that the recycling of CDW produced environmental benefits and economic profits. Simion et al. [7] proved that the CDW recycling process has a low environmental impact, including several advantages such as reduced consumption of non-renewable raw materials, a reduction in the number and size of landfills, and the creation of materials that can replace natural raw materials. According to Vossber et al. [8], onsite CDW recycling can avoid up to 90% of the energy and greenhouse gas (GHG) emissions from landfilling, demonstrating the huge advantages of CDW recycling.

It has been demonstrated that solutions for CDW significantly contribute to material recycling and rational utilization in a circular economy, but they cannot solve all challenges. Another key sector in the circular economy is sustainable concrete production, in which increasing pressure to reduce environmental emissions has created a need to search for new solutions. The issue with concrete production is the high CO_2 emissions caused by the manufacturing of the main cement constituent. According to various estimations, the cement industry is responsible for 5–7% of global CO_2 emissions [9]. A solution to reduce its environmental impact could be to search for alternatives and substitutes for cement constituents, such as filler from secondary material streams. Traditional supplementary materials used in concrete production, such as fly ash and slag, may be restricted in the future because these raw material sources are increasing less rapidly or not at all owing to, environmental pressures. For example, the practice of burning waste for energy recovery is being questioned. Even if the availability of raw materials is not a problem, the treatment method might have a large cost impact, such as calcination in the case of clay [10]. Ash may also contain significant concentrations of potentially leachable heavy metals [11]. Therefore, it is rational to investigate the reutilization of the fine particles from CDW as a supplementary cementitious material, which was demonstrated in a study by Frias et al. [12]. Caetano et al. [13] also reported the good mechanical and physical properties of concrete blocks fabricated by utilizing fine fraction scrap from end-of-life vehicles (ELV). In addition to the environmental and economic advantages of material recycling, various legislative and taxation issues influence the reutilization of CDW, such as the waste management hierarchy, recycling goals, and various administrative action plans for a circular economy.

1.2. Fine Fraction as a Resource

As described in the introduction, it is very important to search for new substitute material solutions from secondary material streams because of potential availability challenges in the future. One certain potential future raw material is the fine fraction from waste management processes; for example, the fine fraction from the treatment of CDW has been estimated to represent 20–50% of the total stream [14]. The heterogeneous nature of fine fraction material has been a restrictive factor for the lack of research. Combining the great share of fine fraction in CDW and the remarkable role of CDW in waste management overall, it can be seen as the real gap in the research of CDW fine fraction. To date, the CDW fine fraction has been used as an alternative barrier in landfills [15], similar to the general fine fraction, and various potential innovations have been studied, such as its employment in green roof applications [16]. The general fine fraction, which consists of soil that originates from degraded organic matter and other small fractions, such as plastic, glass, and metals, is known to represent a major part of landfill composition [17]. In the fine fraction of CDW, the organic content may be minor; however, the assortment of other particles may be wider. The availability of fine fraction materials from sources other than CDW may expand in the future because of their great abundance. The mass percentage of the fine fraction was found to be 38% of the total waste in the case of landfills, but even higher (40–70%) rates have been observed [18]. Mönkäre et al. [19] found shares of 45% and 58% for the fine fraction below 20 mm in the case of landfills in Finland, which is consistent with the global estimation made by Singh and Chandel [20], who stated that approximately 50% of dumped waste can be characterized as fine fraction.

1.3. The Purpose of Study

The purpose of the present study is to evaluate potential applications for the fine fraction from secondary material streams and to study the efficiency of its recovery and recycling. This was achieved by assessing material streams in the selected areas and analyzing their material features using various characterization methods. The study focuses on material characterization, like particle size and shape, elemental composition, and regional availability scenarios, that were not often studied in the previous studies of material science.

2. Materials and Methods

2.1. Material

The study began with a statistical analysis, in which potential raw material streams for fine rejects from the YLVA system for the selected materials were studied. The YLVA (*Finnish: Ympäristönsuojelun valvonnan sähköinen asiointijärjestelmä*) system is subject to an environmental permit or notification obligation under the Environmental Protection Act (527/2014) reporting service that provides for monitoring the activities of the party subject to the permit or notification obligation, which is supervised by authority of the ELY Centre (The Centres for Economic Development, Transport and the Environment). The YLVA system tracks the waste amounts in a database according to the List of Waste (LoW) and the European Waste Catalog (EWC). The review period for the generated raw materials was 2019–2021, and the study was focused on the Kymenlaakso province and nearby areas in southeast Finland, consisting of about 175 000 permanent inhabitants in nine municipalities (Hamina, Iitti, Kotka, Kouvola, Lapinjärvi, Miehikkälä, Mäntyharju, Pyhtää, and Virolahti). According to the population, Kymenlaakso province is one the smallest province in Finland, and therefore actions in the provinces will be effectively scalable because its population density is one the highest. The province has also experienced a loss of migration, so novel innovations in material science are needed for the region. Annual waste amounts were averaged over three years based on the annual amount of waste generated during these three years. A three-year review period will give reliable information as an average because it includes both pre and post-pandemic impacts.

2.2. Material Characterization

After statistical investigation of the availability of the material, physical characterization of the raw materials was performed based on the particle size and shape, and by visual inspection. The raw materials were fine fraction samples obtained randomly from the mechanical separation process of Ekokaari Oy (Kouvola, Finland) after separation of the flip-flop screen. The main particle size of the obtained material was less than 15 mm in diameter, based on the screen's process capacity. The sample size was approximately 100 kg, and it was collected in outdoor conditions during November 2021. After collection, the sample was stored in an unheated and covered storage unit at a temperature below zero (0 °C) before the analysis.

2.2.1. Particle Size Analysis

The particle size and shape distributions of the fine rejects were studied by sieving and shape analyses. Particle size analysis was performed using a HAVER EML 450 sieve shaker (HAVER & BOECKER OHG, Oelde, Germany), in which six vibrating sieves were used to divide the material into seven fractions to determine its particle size distribution. The sieves consist of stainless-steel frames with a medium of woven wire cloth or robust plates with square meshes and sieves with the following opening sizes were used: 200 µm, 500 μm, 800 μm, 1250 μm, 2500 μm, and 5000 μm (from bottom to top), based on a preliminary sieving test using the studied material. A bowl was placed under the smallest screen to collect the particles that passed through it. The sieving was made once where the amplitude was adjusted to the 1.5 mm range at five intervals, and the time was set to 14 min for each material sample in this study. Owing to the three-dimensional sieving motion of the shaker, the material was shaken through the mesh in the vertical direction and distributed over the sieve surface in a circular motion. After screening, each screen was weighed along with the fine fraction inside it.

The effects of size reduction and organic content were also investigated. The influence of size reduction was investigated by crushing the fine fraction using an SK 300 hammer mill (Retsch GmbH, Haan, Germany) at 3000 rpm. The hammer mill was equipped with a screening system, in which a screen with a mesh size of 4 mm was used. The organic content of the material was analyzed by burning 9.9 kg of the material batch with liquefied petroleum gas (LPG) to remove the organic material from the sample. The burning treatment was conducted in six batches on a thin layer of material for 10 min in the same spot within a distance of approximately 10 cm, after which the remaining material was weighed before particle size analyses. The amounts of material in the original, crushed, and burned samples were 4.0, 3.6, and 5.4 kg, respectively. The materials were screened in batches of two or three rounds.

2.2.2. Particle Shape

The particle shapes of five screened material fractions (<200 μm, 200–500 μm, 500–800 μm, 800–1250 μm, 1250–2500 μm) were measured with an L&W Fiber Tester (ABB, Stockholm, Sweden) device, using a dilution of approximately 0.1 g of the studied material in >100 ml of water for a 200 s analysis time. The particle width, length, number of particles, shape factors, and coarseness were determined and recorded as averages. The maximum particle length was 7.5 mm, and objects with a length of <0.2 mm were defined as fine particles. Objects with a length of >0.2 mm and a length-to-width ratio greater than 4 were defined as fiber-shaped. Three samples of each material type and particle size were tested.

2.3. Elemental Analysis

Elemental analyses of the studied materials were performed using a handheld X-ray fluorescence (XRF) analyzer (Hitachi, X-MET8000 Expert, Tokyo, Japan), which nondestructively quantifies the elements in a material. The instrument configuration includes three various pre-programmed settings for different materials, such as light–element alloys, plastic, and wood, which were used for the studied materials. Utilizing various material settings allows wide positive material identification. The results are presented as average values. The XRF analysis was performed for the screened fine fraction with a particle size from 500 μm to 800 μm, and also for concrete-like test samples made from the same material, containing a mix of the fine fraction (particle size 500–800 μm), cement and water, according to the K20 recipe, in which the ratios of cement, fine fraction and water were 1:5:1.3–3.0, correspondingly. The screened fine fraction was analyzed in a sample cup with a diameter of 30.5 mm and height of 19.6 mm, which had been filled approximately three–quarters-full by compression with a circular tool (diameter 28.2 mm) with a weight of 52.1 g at the upper side of the sample cup without extra force. The base of the sample cup was open, and it was covered by a film with a thickness of 4 microns (Poly 4 (L73) Hitachi). The studied materials were the original, size-reduced, and organic-free fine fractions described above. Three samples were prepared from each material category, and each sample was analyzed by three replicates, creating nine results from each pre-programmed configuration. The duration of each XRF measurement was 60 s.

3. Results

3.1. Available Fine Reject Materials

According to a literature review, potential raw material sources for fine rejects are the mechanical treatment of waste, construction and demolition waste, waste from dismantling end-of-life vehicles (ELV), waste from power stations and other combustion plants, and waste from incineration or pyrolysis of wastes. The total amounts of the mentioned wastes in the Kymenlaakso area are presented in **Table 1**. In addition, asphalt has been found to be a source of fine rejects, because approximately 23% of recycled asphalt was classified as small-sized rejects that must be removed from the crushed asphalt owing to quality issues [21].

Table 1. Average annual amounts (kt) of the reviewed materials during the three-year period based on their LoW codes in parentheses.

Waste Type (LoW Code)	Amount (kt)
Waste from power stations and other combustion plants (10 01)	80.6
Waste from dismantling of end-of-life vehicles (ELV) (16 01)	4.9
Construction and demolition waste (17)	307.4
Waste from incineration or pyrolysis of waste (19 01)	75.5
Waste from the mechanical treatment of waste (19 12)	153.3
Asphalt	2.8

Asphalt generation was minor, and according to the YLVA system, asphalt is included in the CDW (17) catalog; therefore, its generation and analysis as a separate raw material source were dismissed.

Cossu and Lai [22] reported that approximately 20–25% of ELV processing includes automotive shredder residue (ASR), which is a heterogeneous and complex matrix that is largely landfilled. The reviewed statistics show that the amount of waste generated by dismantling vehicles varied from 3717 to 6485 tons per year in the selected areas, including a large share of hazardous waste. Owing to the small volume of the material streams in the studied areas, waste from ELV dismantling was not considered in depth as a potential raw material source for fine rejects. However, ASR could be a potential material source for a wider survey. The number of ELVs in the review area (Kymenlaakso) was minor, for example, 2599 pc in 2020 [23], which corresponds to approximately 3% of the total amount in Finland in the same year [24]. In the case of ELV, various campaigns to promote vehicle recycling have been active in recent years, which may increasingly influence the amount of ELV. Globally, the significance of ASR should not be underestimated; according to one estimate, more than 25 million vehicles worldwide become ELVs every year [13].

3.2. Features of Particles

Different material analyses were employed to examine the features of the fine rejects, including visual analysis, particle size and shape measurements, and elemental composition analysis. Two 100 g sample batches were analyzed by visual inspection. The batches were selected randomly by mixing the material before sample collection to ensure a reliable distribution of different fractions. The batch was spread on an empty table, and before the actual visual classification, ferrous metal was removed from the batches using a magnet. After classification, a total of 18 material groups were identified in the studied material, including ferrous metal and fine material with a small particle size material that could not be properly identified, which was composed of the remaining material after the classification of the larger particles. Based on this identification process, the description of the material groups included the following particles: Asphalt, Brick, Ceramic, Concrete, Electric wire, Ferrous metal, Fine material, Glass, Gypsum, Plastic (hard and soft), Rubber, Styrofoam, Stone, Textile, Unidentified, Wood, Wool.

Figure 1 illustrates the particle size distribution of the studied materials; the results are presented as bar charts with fifth-order polynomial trend lines and indicate clear differences between the materials. The results showed that the dominant particle size of the original material was over 5 mm, while size reduction decreased the dominant particle size to 500–800 µm. A higher particle size distribution in the original material indicates a higher porous material content. The organic-free material contains fine particles (<200 µm) as well as coarse particles (>5 mm), but it has a more equal distribution among various particle sizes compared to the original and size-reduced samples, in which one particle size class was predominant. The predominantly small particle size will lead to a higher specific surface area, which will influence the raw material features and the later use of the materials. Jani et al. [18] showed that 80% of the excavated waste in landfills was smaller than 2 mm, which appears to be consistent with the size-reduced fine fraction in our study and other categories representing a larger particle size distribution.

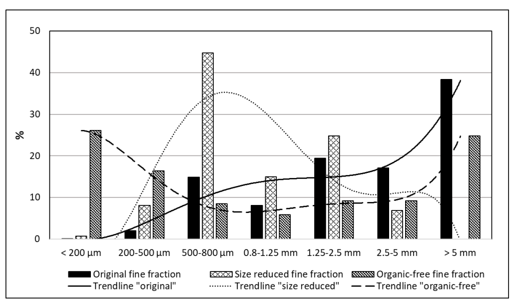

Figure 1. Particle size distribution for various fine rejects.

Particle shape analyses, including the average values of the length-to-width ratio and number of fibers in the material sample, are shown in **Figure 2**, which includes bar charts with fifth-order polynomial trend lines. The trend lines for the results of the length/width (L/W) ratio are presented as solid lines, and the trend lines for the results of the fiber numbers are presented as dotted lines. The results are presented numerically, with the number of fiber values presented by italics to distinguish them from the L/W ratio values. The results showed that organic-free treatment had a significant effect on the properties by increasing the L/W ratio and number of fibers, especially in the case of small particles, for which the proportion (1739 fibers) was significantly high. The highest L/W ratio was detected in the 0.5–0.8 mm particle size class, for which the L/W ratio was 67.8. The smallest L/W ratio (25.4) in the organic-free sample was observed for the smallest particles; this ratio was higher than almost all the L/W ratio results for the original and size-reduced samples, with only the largest particle size class (1.25–2.5 mm) having a higher L/W ratio. It has been demonstrated that generally, increased length correlates positively with strength properties, although the weight ratio also affects these properties [25]. In addition, excessive length results in decreased strength [26].

The total number of fibers was similar in the original and organic-free fractions, but size reduction decreased the number of fibers. There were no remarkable differences in the particle shape between the original and size-reduced fine fraction samples. Both samples had increased L/W ratios with increasing particle size categories, but this tendency was slightly stronger for the original fine fraction sample.

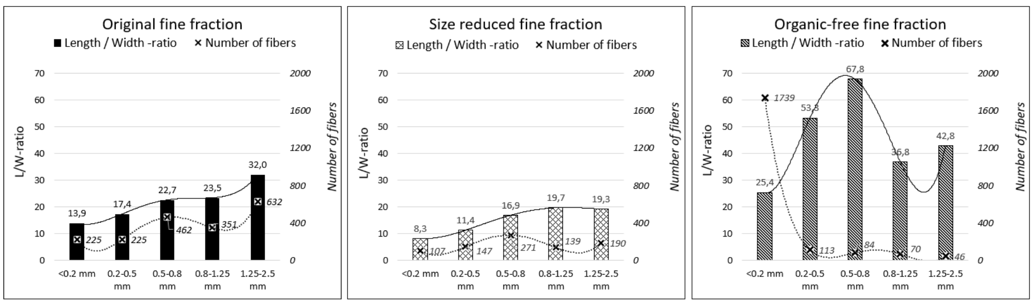

Figure 2. L/W ratios and number of fibers in the various fine rejects.

3.3. Elemental Composition of Fine Rejects

The unequivocal elemental composition results are presented based on the plastic material preprogrammed settings in **Table 2**, which represents the best average values among those measured. The plastic preprogrammed settings were the most appropriate settings for the studied material compared to the wood material and the light element alloys settings. The results obtained using the preprogrammed wood material setting were quite like the plastic results, but with a narrower range of detected elements. The results for the light element alloys demonstrate that higher values of the entire composition do not seem to be rational.

Table 2. Elemental composition of the samples obtained using XRF analysis; values are expressed in wt%. The studied materials were the original fine fraction (OFF), size-reduced fine fraction (SFF), and organic-free fine fraction (FFF), as well as the manufactured concrete-like materials of those materials, denoted as by C-OFF, C-SFF, and C-FFF, correspondingly. The content's illustration was highlighted by shading colors as follows: ≥5% = plum, <5%–≥1% = orange, <1%– ≥0.10% = blue, <0.10% = green.

The highest elemental contents were measured for calcium (Ca) and iron (Fe), whose composition varied from 2.81 to 6.55 and from 2.34 to 7.78 wt%, respectively, in the fine fraction samples. The proportional shares of both elements were maintained in the organic-free treatment, while their absolute shares were approximately doubled compared with those in the original and size-reduced materials. The presence of calcium (Ca) might indicate CDW-based raw material source, such as cementitious material. The presence of ferrous (Fe) support CDW source, because it might originate the rebar of reinforced concrete, or from other construction clips. In concrete-like materials, the amount of calcium increased due to the cement binder. Zinc (Zn) was the element with the third-highest detected content in the sample but was clearly a minor component compared to Ca and Fe, with its content varying from 0.30 to 0.60 wt%. Zn may originate from additives, along with titanium (Ti) and barium (Ba), which are the most abundant additive elements in the product. Overall, the observed elemental composition was quite minor, and no critical observations were made. Comparing these elemental composition results with those of Kaartinen et al. [27], who analyzed the concentrations elements from the fine fraction of municipal solid waste (MSW), we can see that many of elements have similar or slightly lower concentrations in our study. Some elements, such as Fe, Ba, and Zn, have higher concentrations in the present study; however, these elements might be typical additives in construction materials. The high concentrations of these elements can be beneficial, because they may increase interest in fine fractions for element recovery in the future.

Table 2. Elemental composition of the samples obtained using XRF analysis; values are expressed in wt%. The studied materials were the original fine fraction (OFF), size-reduced fine fraction (SFF), and organic-free fine fraction (FFF), as well as the manufactured concrete-like materials of those materials, denoted as by C-OFF, C-SFF, and C-FFF, correspondingly. The content's illustration was highlighted by shading colors as follows: ≥5% = plum, <5%–≥1% = orange, <1%– ≥0.10% = blue, <0.10% = green.

Element	OFF	SFF	FFF	C-OFF	C-SFF	C-FFF
Cl	0.15 ± 0.03	0.17 ± 0.04	0.53 ± 0.07	-	-	-
Ca	2.96 ± 0.12	2.81 ± 0.13	6.55 ± 0.41	15.11 ± 0.67	13.23 ± 0.87	15.84 ± 1.28
Ti	0.11 ± 0.01	0.11 ± 0.01	0.66 ± 0.09	0.14 ± 0.02	0.15 ± 0.01	0.17 ± 0.05
Cr	0.03 ± 0.01	0.01 ± 0.00	0.03 ± 0.03	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.01
Mn	0.04 ± 0.00	0.03 ± 0.00	0.06 ± 0.01	0.05 ± 0.01	0.04 ± 0.01	0.03 ± 0.00
Fe	3.57 ± 0.14	2.34 ± 0.14	7.78 ± 1.10	3.99 ± 0.34	3.12 ± 0.23	3.02 ± 0.17
Ni	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.01	0.00 ± 0.00
Cu	0.09 ± 0.00	0.19 ± 0.13	0.20 ± 0.04	0.08 ± 0.01	0.12 ± 0.06	0.27 ± 0.24
Zn	0.37 ± 0.02	0.30 ± 0.09	0.60 ± 0.08	0.35 ± 0.04	0.35 ± 0.17	0.32 ± 0.09
Br	0.00 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.00 ± 0.00	0.01 ± 0.00	0.00 ± 0.00
Sr	0.03 ± 0.00	0.03 ± 0.00	0.07 ± 0.01	0.04 ± 0.00	0.04 ± 0.00	0.04 ± 0.01
Zr	0.02 ± 0.00	0.02 ± 0.00	0.04 ± 0.02	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.03
Sn	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00
Sb	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00
Ba	0.12 ± 0.01	0.12 ± 0.01	0.25 ± 0.03	0.13 ± 0.02	0.12 ± 0.00	0.16 ± 0.02
Pb	0.04 ± 0.00	0.03 ± 0.01	0.12 ± 0.09	0.05 ± 0.01	0.03 ± 0.00	0.03 ± 0.01

4. Discussion

CDW is a key source of fine rejects; for example, Nasrullah et al. [28] stated that 28% of CDW can be classified as a fine fraction. This statement is consistent with the report of Laine-Ylijoki et al. [29], who stated that 20–40% of CDW is ground into fine particles during material processing, generating 130,000–270,000 tons of CDW fine rejects per year in Finland. The share of CDW in the studied area was remarkable, varying between 270,379 and 349,727 tons per year, without hazardous waste materials. In the assessment of potential fine rejects, we considered the waste category "17 09 04 mixed construction, and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03." The total amount over the three-year period varied from 31,900 to 36, 400 tons, indicating the generation of 9679 tons of fine rejects as the average yearly amount.

The mechanical treatment of waste can provide a potential raw material source for fine rejects. Based on previous observations, one-quarter of these materials are fine reject materials. Based on the YLVA database, the amount of waste generated from the mechanical treatment of waste (EWC 19 12) without hazardous content varied from 132,790 to 176,173 tons yearly in the reviewed area. This category includes various types of waste materials, but the most feasible source of fine rejects is the waste category "Other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11" (EWC 19 12 12). The average annual production for this category is 4046 t, as calculated by taking a quarter of the total amount. However, significant variations (from 774 to 6485 tons) were observed during the review period of 2019–2021.

According to the raw material review, the most abundant potential raw material sources for fine rejects are construction and demolition waste and waste from the mechanical treatment of waste. A minor uncertainty factor for the evaluation of the amount of material generated is the wide variation in the percentages of waste classified as fine fraction for a given waste category, such as the fine reject share of CDW, which varies from 20 to 40% of the total amount according to Laine-Ylijoki et al. [29]. Therefore, we created three scenarios (standard, weak, and superior) for fine reject availability in Kymenlaakso, for which we used the two extreme rates (20% and 40%) in addition to the so-called standard rate of 28%, based on the report of Nasrullah et al.[28]. The lowest fine fraction share value in the literature was reported by López-Uceda et al.[16], who found that the fine fraction comprises 13.5% of the recycled aggregates produced from CDW. However, the presented evaluation of the fine reject share is also consistent with the report of Jani et al.[18], in which the fine fraction represented 38% of the total excavated waste in landfills in Sweden. In addition, our scenarios also include the extreme rates for waste from mechanical treatment. The scenarios are presented in **Table 3**, which shows that in a standard year, over 13,000 tons of usable fine rejects were generated in the reviewed areas, with a variation of approximately 6500 tons in either direction. Like it was mentioned, the studied region (Kymenlaakso province) includes about 175,000 permanent inhabitants, which represents about below 3% of Finland population. Therefore, the national effect of fine reject source could be approximately 35-fold in Finland, and multiply if we would extend to the study area more globally.

Table 3. Scenarios of fine reject availability in Kymenlaakso in tons per year, as an average, with LoW codes in parentheses.

Scenario	CDW	Mechanical Treatment Waste (19 12)	Total
1. Standard (28% of EWC 17 + average of EWC 19 12)	9 679	4 046	13 725
2. Weak (20% of EWC 17 + the weakest year of EWC 19 12)	6 375	774	7 149
3. Superior (40% of EWC 17 + the best year of EWC 19 12)	14 145	6 485	20 630

In addition to the aforementioned fine reject sources, waste from various combustion and incineration sources are also a potential raw material for fine rejects with similar features. These materials are classified in the YLVA database as "Wastes from power stations and other combustion plants" (EWC 10 01) and "Wastes from incineration or pyrolysis of waste" (EWC 19 01), and the amounts of these wastes produced without hazardous substances in the Kymenlaakso area varied yearly from 92,097 to 154,082 tons. Traditionally, ash has been utilized in different applications and has also been dumped in landfill sites; which is neither a sustainable nor an economically feasible solution[30]. The total average annual amount of material generated is high, as shown in **Table 1**, but the boiler and fly ash waste from the incineration or pyrolysis of waste includes a remarkable number of hazardous materials. However, there is scope for combustion-produced ash (bottom and fly ash) to be utilized more effectively, although the utilization ratio of ash varies globally from 50% to 90%, the practical utilization rate is only 30%[31]. Fly ash is traditionally used in concrete production, road base construction, soil amendment, zeolite synthesis, and as a filler in polymers. However, these applications are insufficient for complete utilization[31] and the quality of fly ash as a cementitious material varies[10]. The total amount of ash generated in Finland is significant, at almost 1.5 million tons per year[32]; thus, its potential as a raw material is remarkable. In addition, global power generation is estimated to increase as the demand for cheap power increases in developing countries[33].

The fine fraction has a high absorption capacity, which may result in the loss of features in concrete production. On the other hand, if fine fraction includes elongated particle shapes (L/W ratio) with a high number of particles, as in the original fine fraction source, it can improve strength features in concrete. Thus, there is a need for future studies on the mechanical properties of fine fraction and its effect on concrete manufacturing. For example, various hybrid product applications could provide solutions for the fine fraction use. The biggest restriction for the reutilization of fine fractions might be economic issues, because virgin materials have high availability and low cost, decreases interest from developing businesses. Therefore, the scale of the solution must be large in order to achieve tangible effects. The cost of fine fraction will not restrain its use as a raw material, but the economic challenges might be created by treatment steps that might cause limitations for economic feasibility and restrain industrial adoption. Importantly, all treatments for fine fractions have economic effects, such as current options, in which the fine fraction from landfills must be treated by anaerobic or aerobic treatment to reduce its organic content at a cost of 20–65 euros per ton[17]. In comparison, the utilization of fine fraction as a material additive can be an economical alternative. In the case of landfill mining, Jones et al.[34] stated that economic benefits must outweigh costs in order to increase the interest of individual companies. This statement from a decade ago remains valid for the CDW fine fraction today.

Population (below 200000 in the Kymenlaakso area) could be a good correlate for the estimated value of fine fraction produced. However, population is not a clear indicator of the fine fraction amount, because markets can consider materials from other areas. In addition, various seasonal variations, such as production constraints and regular holiday periods, may affect the amount of waste produced. One clear advantage of fine fraction use is its readiness as a material, which makes it more economical. Assaad and Mardani [35] stated that the use of recycled fine aggregates as a porous material required 22–30% less energy need for process in cement production compared to the traditional production process. Using the fine fraction from the mechanical separation process, the energy savings could be even higher, thereby indicating the need for future research on this topic. The fine fraction, as a raw material, contributes to low density and thermal conductivity, providing advantages in terms of transportation and energy savings [20].

5. Conclusions

Circular economic activities such as resource-efficient material recycling have become popular in recent times. The focus has often been on large material particles, even though the fine fraction accounts for a high percentage of the total secondary material stream. This study focused particularly on the utilization of the CDW fine fraction, for which recycling alternatives are lacking; therefore, its availability and characterization must be studied. The availability of the fine fraction of CDW in the Kymenlaakso area was assessed, and its material features were experimentally analyzed.

Various substitute secondary raw sources include potential materials for production; however, their scattered distribution may present a challenge, making their economic viability questionable. Therefore, the assembled available fine fraction could be profitable material in the future, because its reutilization appears to be very rational. Reutilization of the fine fraction will presumably generate environmental and economic benefits in addition to increasing the recycling rate. This study has demonstrated that a certain availability level of the CDW fine fraction is guaranteed in the selected area, and it could be expanded using other material streams. A certain degree of heterogeneity was observed in the investigated materials, but the results show that sorting and treatment mechanisms for the materials are rational for reutilization purposes, allowing their use as potential raw materials in the future and avoiding a downcycling effect. For example, 0.5–0.8 mm particle size class can be easily achieved by size reduction treatment when over 5 mm is the dominant particle size in original fine fraction material. Potential future directions for CDW fine fractions include:

- assessment of their mechanical features in hybrid materials and product prototypes and
- holistic sustainability assessments of its processes during life cycle.

For example, using fine fraction as a substitute in cast products may decrease the need for a binder agent, contributing to a reduction in emissions.

Author Contributions

Conceptualization, V.L. and I.R.; methodology, I.R.; software, V.L.; validation, V.L.; formal analysis, V.L.; investigation, I.R.; resources, V.L.; data curation, I.R.; writing—original draft preparation, V.L.; writing—review and editing, I.R. and T.K.; visualization, V.L.; supervision, T.K.; project administration, V.L.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

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The authors declare that data will be available on a request.

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Jin, R., Yuan, H., Chen, Q., 2019. Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018. Resources, Conservation & Recycling. 140, 175-188. DOI: https://doi.org/10.1016/j.resconrec.2018.09.029

[2] Mosche-Schimek, J., Kapser, T., Huber-Humer, M., 2023. Critical review of the recovery rates of construction and demolition waste in the European Union - An analysis of influencing factors in selected EU countries. Waste Management. 167, 150-164. DOI: https://doi.org/10.1016/j.wasman.2023.05.020

[3] Lopez Ruiz, L.A., Ramon, X.R., Domingo, S.G., 2020. The circular economy in the construction and demolition waste sector - A review and an integrative model approach. Journal of Cleaner Production. 248, 119238. DOI: https://doi.org/10.1016/j.jclepro.2019.119238

[4] Zhang, C., Hu, M., Di Maio, F., et al., 2022. An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Science of the Total Environment. 803, 149892. DOI: https://doi.org/10.1016/j.scitotenv.2021.149892

[5] Kabirifar, K., Mojtahedi, M., Wang, C., et al., 2020. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. Journal of Cleaner Production. 263, 121265. DOI: https://doi.org/10.1016/j.jclepro.2020.121265

[6] Dahlbo, H., Bacher, J., Lahtinen, K., et al., 2015. Construction and demolition waste management - a holistic evaluation of environmental performance. Journal of Cleaner Production. 107, 333-341. DOI: http://dx.doi.org/10.1016/j.jclepro.2015.02.073

[7] Simion, I.M., Fortuna, M.E., Bonoli, A., et al., 2013. Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA. Journal of Environmental Engineering and Landscape Management. 21, 273-287. DOI: https://doi.org/10.3846/16486897.2013.852558

[8] Vossberg, C., Mason-Jones, K., Cohen, B., 2014. An energetic life cycle assessment of C&D waste and container glass recycling in Cape Town, South Africa. Resources, Conservation & Recycling. 88, 39-49. DOI: http://dx.doi.org/10.1016/j.resconrec.2014.04.009

[9] Oliveira, T.C.F., Dezen, B.G.S., Possan, E., 2020. Use of concrete fine fraction waste as a replacement of Portland cement. Journal of Cleaner Production. 273, 123126. DOI: https://doi.org/10.1016/j.jclepro.2020.123126

[10] Scrivener, K., Martirena, F., Bishnoi, S., et al., 2018. Calcinated clay limestone cements (LC3). Cement and Concrete Research. 114, 49-56. DOI: https://doi.org/10.1016/j.cemconres.2017.08.017

[11] Bourtsalas, A., Vandeperre, L.J., Grimes, S.M., et al., 2015. Production of pyroxene ceramics from the fine fraction of incinerator bottom ash. Waste Management. 45, 217-225. DOI: http://dx.doi.org/10.1016/j.wasman.2015.02.016

[12] Frías, M., de la Villa, R.V., Martínez-Ramírez, S., et al., 2020. Multi-Technique Characterization of a Fine Fraction of CDW and Assessment of Reactivity in a CDW/Lime System. Minerals. 10, 590. DOI: https://doi.org/10.3390/min10070590

[13] Caetano, J.A., Schalch, V., Pablos, J.M., 2020. Characterization and recycling of the fine fraction of automotive shredder residue (ASR) for concrete paving blocks production. Clean Technologies and Environmental Policy. 22, 835-847. DOI: https://doi.org/10.1007/s10098-020-01825-y

[14] Martins, I., Müller, A., di Maio, A., et al., 2013. Use of Fine Fraction. In: Vázquez, E. (eds.) Progress of Recycling in the Built Environment, Springer Dordrecht: Dordrecht, The Netherlands. pp. 195-227.

[15] Correia, N.S., Caldas, R.C.S., Oluremi, J.R., 2020. Feasibility of using CDW fine fraction and bentonite mixtures as alternative landfill barrier mate-

rial. Journal of Material Cycles and Waste Management. 22, 1877-1886. DOI: https://doi.org/10.1007/s10163-020-01075-6

[16] López-Uceda, A., Galvín, A.P., Ayuso, J., et al., 2018. Risk assessment by percolation leaching tests of extensive green roofs with fine fraction of mixed recycled aggregates from construction and demolition waste. Environmental Science and Pollution Research. 25, 36024-36034. DOI: https://doi.org/10.1007/s11356-018-1703-1

[17] Mönkäre, T., Palmroth, M.R.T., Sormunen, K., et al., 2019. Scaling up the treatment of the fine fraction from landfill mining: Mass balance and cost structure. Waste Management. 87, 464-471. DOI: https://doi.org/10.1016/j.wasman.2019.02.032

[18] Jani, Y., Kaczala, F., Marchand, C., et al., 2016. Characterisation of excavated fraction and waste composition from a Swedish landfill. Waste Management and Research. 34, 1292-1299. DOI: https://doi.org/10.1177/0734242X16670000

[19] Mönkäre, T.J., Palmroth, M.R.T., Rintala, J.A., 2016. Characterization of fine fraction mined from two Finnish landfills. Waste Management. 47, 34-39. DOI: http://dx.doi.org/10.1016/j.wasman.2015.02.034

[20] Singh, A., Chandel, M.K., 2022. Valorization of fine fraction from legacy waste as fired bricks: A step towards circular economy. Journal of Cleaner Production. 331, 129918. DOI: https://doi.org/10.1016/j.jclepro.2021.129918

[21] Naukkarinen, E., 2020. Crushed Tarmac Reuse in Structural Layers. Oulu University of Applied Sciences. Available from: https://urn.fi/URN:NBN:fi:amk-2020060316657 (cited 28 June 2023).

[22] Cossu, R., Lai, T., 2015. Automotive shredder residue (ASR) management: An overview. Waste Management. 45, 143-151. DOI: http://dx.doi.org/10.1016/j.wasman.2015.07.042

[23] The Finnish Information Centre of Automobile Sector, 2023. Statistics. Number of certificates of destruction. Available from: https://www.aut.fi/en/statistics/statistics_of_scrapped_vehicles/number_of_certificates_of_destructions_yearly (accessed 10 August 2023).

[24] Environment.fi, 2022. (Joint website of Finland's environmental administration) Romuajoneuvotilastot, päivitetty 15.7.2022. Available from: https://www.ymparisto.fi/fi-fi/kartat_ja_tilastot/jatetilastot/tuottajavastuun_tilastot/Romuajoneuvotilastot (cited 22 December 2022).

[25] Khakpour, H., Ayatollahi, M.R., Akhavan-Safar, A., et al., 2020. Mechanical properties of structural adhesives enhanced with natural date palm tree fibers: Effects of length, density and fiber type. Composite Structures. 237, 111950. DOI: https://doi.org/10.1016/j.compstruct.2020.111950

[26] Dabade, B.M., Reddy, G.R., Rajesham, S., et al., 2006. Effect of fiber length and fiber weight ratio on tensile properties of sun hemp and palmyra fiber reinforced polyester composites. Journal of Reinforced Plastics and Composites. 25, 1733-1738. DOI: https://doi.org/10.1177/0731684406068418

[27] Kaartinen, T., Sormunen, K., Rintala, J., 2013. Case study on sampling, processing and characterization of landfilled municipal solid waste in the view of landfill mining. Journal of Cleaner Production. 55, 56-66. DOI: http://dx.doi.org/10.1016/j.jclepro.2013.02.036

[28] Nasrullah, M., Vainikka, P., Hannula, J., et al., 2014. Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste. Waste Management. 34, 2163-2170. DOI: http://dx.doi.org/10.1016/j.wasman.2014.06.009

[29] Laine-Ylijoki, J., Castelli-Rüdenhausen, M., Kaartinen, T., et al., 2018. Report on the situation of the treatment capacity of certain wastes and rejects and the market of some waste-based materials in Finland.

[30] Sormunen, L.A., Rantsi, R., 2015. To fractionate municipal solid waste incineration bottom ash: Key for utilisation? Waste Management and Research. 33, 995-1004. DOI: https://doi.org/10.1177/0734242X15600052

[31] Yao, Z.T., Ji, X.S., Sarker, P.K., et al., 2015. A comprehensive review on the applications of coal fly ash. Earth-Science Reviews. 141, 105-121. DOI: http://dx.doi.org/10.1016/j.earscirev.2014.11.016

[32] Arnkil, N., Joensuu, S., Kauppila, M., et al., 2020. Tuhka osana kestävää liiketoimintaa - Opas tuhkan tuottajille ja käyttäjille. Tapion raportteja 42. Tapio Oy: Helsinki, Finland.

[33] Dindi, A., Quang, D.V., Vega, L.F., et al., 2019. Applications of fly ash for CO2 capture, utilization, and storage. Journal of CO2 Utilization. 29, 82-102. DOI: https://doi.org/10.1016/j.jcou.2018.11.011

[34] Jones, P.T., Geysen, D., Tielemans, Y., et al., 2013. Enhanced Landfill Mining in view of multiple resource recovery: a critical review. Journal of Cleaner Production. 55, 45-55. DOI: https://doi.org/10.1016/j.jclepro.2012.05.021

[35] Assaad, J.J., Mardani, A., 2023. Limestone replacements by fine crushed concrete and ceramic wastes during the production of Portland cement. Journal of Sustainable Cement-Based Materials. 12, 1447-1459. DOI: https://doi.org/10.1080/21650373.2023.2225189