



## Technical and environmental properties of recycled aggregates produced from concrete sludge and excavation materials

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### ABSTRACT

This study presents a Re-Con Zero dry washing technology used to produce recycled aggregates from concrete sludge (RCZ) and combined as a feedstock in wet recycling excavation materials (EM) for unbound applications. A two-component admixture i.e. high water absorbing polymer and aluminum sulphate was used in producing RCZ. RCZO, RCZ50 and RCZ100 were produced with EM within the range 0–100%. Analysis by the Los Angeles (LA) and micro-Deval (MD) test demonstrated RCZ to be of high-quality, hence a clear trend of improved performance as the content increased was observed in the LA and MD values. X-ray diffraction analysis performed on original and pulverized residues (<1.6 mm) showed that feldspar, quartz, phyllosilicates (mica and chlorite) and minor amounts of pyroxene (diopside) were present together with paste minerals such as portlandite and residual clinker, and calcite. Acid solubility results demonstrated the relation to increased paste content as particle size reduced. This observation was more prevalent in < 1.6 mm RCZ fraction which further indicated the significant amount of remained paste after wet treatment. Low levels of the content of chemical species of potential concern were in general found and were mostly complying to Norwegian regulations. Total Cr exceeded the criteria of 100 mg/kg, but the leachable Cr(VI) was not detected which showed that remaining Cr after recycling process was present mostly on the trivalent form. This indicated low leaching of Cr upon carbonation and a decrease in pH.

### 1. Introduction

Construction and demolition waste (C&DW) is one of the largest solid waste stream on a global scale [1,2]. The composition of C&DW varies from country to country due to economic structure, environmental and construction policies [1], and about 70–80% of total waste is composed of concrete and bricks [3]. Today, recycling C&DW waste into recycled aggregates is a common practice as it reduces the exploit of aggregate reservoir and environmental pollution [4,5]. Currently, there is a wide range of technological methods which can be applied to process recycled aggregates from C&DW. Many demonstrations have been conducted for the past 15–20 years [6,7], and many significant developments in applying final products have been achieved. For example, considering their application in fresh concrete, some authors have reported stabilized mechanical and durability performance [8,9].

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In order to further increase circular economy, the Norwegian concrete industry is developing solutions to recycle aggregates derived from returned concrete sludge (RCSA). By definition, concrete sludge or returned concrete is residual concrete which remains in the mixing truck and by nature appears in fresh condition with a significant amount of cement mortar [10,11]. Globally, it is estimated that over 125 million tons of these wastes are produced annually depending on quality control during production and use in construction [12]. Currently in Norway, returned concrete are discharged and treated in sedimentation basins, temporarily stored, and finally disposed in a landfill. While one recoverable product is generally known to be RCSA [13], a summary of management strategies to process the waste has been outlined as (a) Recycling in new downgraded products by a process of delivering fresh concrete for pre-cast concrete products or use in backfilling. (b) Reuse in new batches of concrete mixture with or without chemical admixtures or additives. (c) Recycling after hardening of fresh concrete waste by crushing into recycled concrete aggregates (RCA). (d) Reclaiming by a wash-out process using mechanical aggregate reclaiming system to reclaim aggregates and grey water [13]. The outlined management strategies for treatment vary in different countries and are also linked to economic and environmental and logistics issues [13–15].

New emphasis on turning returned concrete into aggregates has been the use of non-toxic additives. For example, one study converted returned concrete into RCSA by using a polymer with high water binding capacity (dosage of 0.4–0.8 m<sup>3</sup> of concrete) and thereafter aluminum sulphate to further enhance the water binding process by ettringite formation. The RCSA was produced in the mixer of a concrete truck with the objective of dry washing the drum. The performance in concrete by 30% replacement to natural aggregates was good, i.e., no significant difference between RCSA concrete and reference concrete regarding water permeable capacity, compressive strength development, water absorption, frost resistance and chloride penetration [11]. The authors, however, mentioned that the interface transition zone of concrete produced with RCSA improved and this contributed to the resistance to water penetration. Similar procedure of applying dry washing technology with high water absorbing polymers has gained interest in Norway and a study demonstrated the Los Angeles strength of RCSA to be 25% by applying this type of polymer [16].

Some studies have also demonstrated the possibility to cease cement hydration of RCSA and to prolong its fresh state using stabilizing additives and activators to allow for reuse in new concrete [17–19]. In other studies, RCSA have been produced by conventional curing and separation of aggregates from waste source. These studies replaced RCSA with natural aggregates in a new concrete at various levels and only a slight decrease in durability properties and almost same strength development was found [20,21]. However, reduced strength development has been reported for concrete with 25–100% RCSA [22,23]. So far, the performance of concrete seems to be dependent on the replacement level of natural aggregates with RCSA and the initial quality. This means that careful control of the substitution level and curing of the sludge are essential to achieve desired properties. Furthermore, the same precautions applying to the use of recycled materials (from regular concrete waste) need to be taken for RCSA. While recycled aggregates from concrete waste is also known for unbound construction, the use of RCSA for the same purpose is not widely considered. A few studies have reported their behavior for similar applications. For example, a study that investigated the use of fine RCSA which was incorporated into mortar for soil stabilization reported increased bearing capacity of the mix [20]. In Norway, a large pilot demonstrated the use of RCSA in road base layer as one of the first of its kind [24].

Failing to demonstrate the extended use of these materials in unbound construction may limit the opportunity to achieve current sustainable targets for the concrete industry. Hence, in the present study a new method for producing recycled aggregates by recycling a mix of concrete sludge and excavation materials was demonstrated. The recycled concrete sludge used in the study has been developed by a two-component admixture Re-Con Zero Evo (high water absorbing polymer and aluminum sulphate). The objective was to use Re-Con Zero dry washing technology to produce recycled aggregates from concrete sludge (RCZ) [25] in combination with wet recycling of excavation materials. To the authors best knowledge, this combined approach has not been reported before, including a technical assessment of the recycled materials separately and in mixed conditions. The present study is part of the RECONC project ([www.reconc.no](http://www.reconc.no)) with the objective of developing RCZ with a lower CO<sub>2</sub> footprint and reduced heavy metal leaching.

## 2. Materials and methods

### 2.1. Preparation of RCZ

RCZ was produced using a dry wash method for cleaning returned concrete from concrete mixer trucks [25]. In this method, aggregates were fed into concrete mixer trucks containing the sludge and rotated a number of times until the sludge appeared to adhere onto the aggregates. They were later poured from the barrel of the truck. The process was repeated in another scenario with other concrete trucks. This method has the advantage of reducing the volume of water used while cleaning the concrete mixer truck and subsequently reducing the pH of the water. In addition, the process reduces the amount of sludge in the sedimentation basins on the concrete batching plants. By adopting this procedure, granular RCZ was produced. Specifically, 4000–6000 L 4/8 aggregates were fed into a hopper and 2000 L of the aggregates was transferred into a concrete truck containing 500 L of return concrete. The drum of the concrete mixer truck was rotated for 3–5 min before the contents were emptied into a storage bin. The entire process took around 15 min. The dry washing aggregates were stored for 8–12 h before larger agglomerates were crushed with a front loader. Following this the aggregates were moved into a separate storage bin and used for feeding the hopper to enter the next dry washing cycle. The dry washing aggregates were used in subsequent cycles until the surface of the aggregate appeared like a sludge surface and saturated. The feedstock derived from this approach was processed at Ølen Betong and sampled at two different places. The first sampling denoted as (RCZ-F<sub>0</sub>) took place at Ølen Betong. The feedstock was transported and stockpiled outside the concrete recycling facility at Velde where the second sample of the feedstock (RCZ-F) was collected. The rest of the materials were converted into recycled aggregates (see Section 2.2).

## 2.2. Production of recycled aggregates

The (CDE, Northern Ireland) recycling plant installed at Sandnes (Norway) was used to recycle and produce the RCZ and excavation materials. It has an operation capacity of processing 350 tons per hour of excavation materials or C&DW. The materials are produced in different fractions 0/2 mm, 2/4 mm, 4/16 mm, 16/32 mm, 20/100 mm, including a residual fraction of  $<63 \mu\text{m}$ . The primary scalping unit with a grizzly feeder of 100 mm opening grid, receives the feedstock, screens, and separates the large materials or boulders. Hence, masses  $< 100 \text{ mm}$  are transported to the log-washer where they are intensely washed and scrubbed. During this process, the in-built over band magnet traps ferrous metals and any lightweight floating material is dewatered and separated through another chamber. The materials are further dewatered and separated into different fractions before passing through secondary magnetic separation. Final processed fractions appear in sizes described above. One benefit of this technology is that more than 90% of processed water is recycled and pumped back into the system for reuse. The processing of 15 tons of waste excavation materials and 15 tons of RCZ was conducted in a full-scale trial at the Velde facility where the final recycled aggregates were sampled directly from the conveyor belts as shown in Fig. 1. The plant was operated without feeding for 10 min before and in between feeding the target materials to avoid cross contamination.

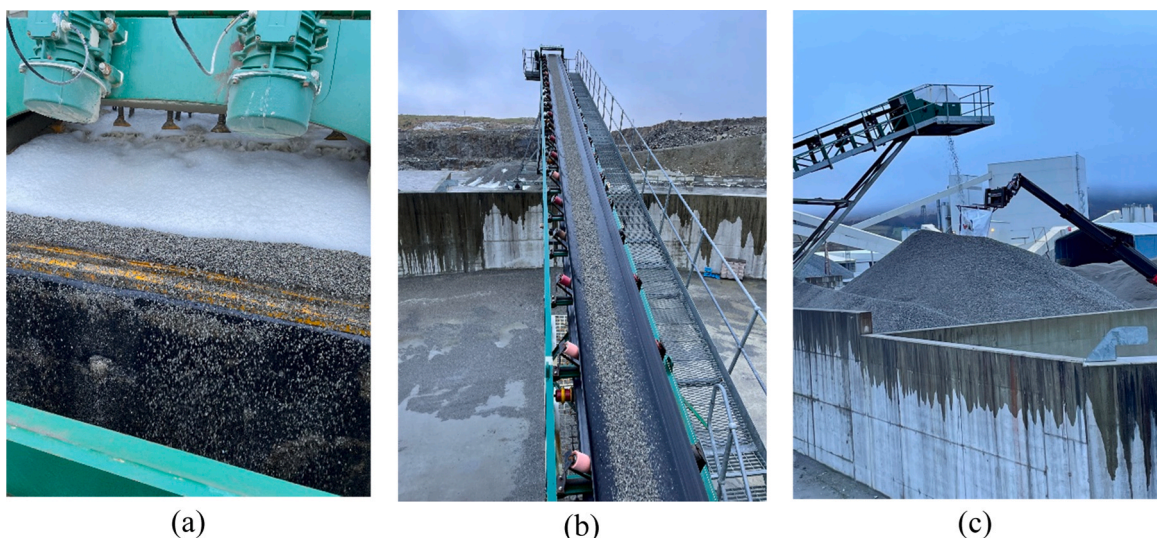
The mixing volumes in the feeding and the samples (final recycled aggregates) collected from the end of conveyor belt are shown in Table 1. Samples denoted RCZ0, RCZ50 and RCZ100 have been produced with 0–100% of excavation materials. The feeding was conducted by a front loader by equal load distribution. Three samples were also collected from the feedstock piles RCZ-F<sub>0</sub>, and RCZ-F. For processed materials, six samples were collected from the 4/16 mm conveyer belt. The materials investigated in the study are shown in Fig. 2.

## 2.3. Physical and mechanical tests

The laboratory experiments comprised of physical, mechanical, and chemical tests. Tests for physical properties were particle-size distribution (NS-EN 933–1), particle density, and water absorption (NS-EN 1097–6). Both particle density and water absorption (WA) were performed on fractions passing through 31 mm sieves but retained on 4 mm. The mechanical tests comprised of LA (NS-EN 1097–2) and MD tests (NS-EN 1097–1). Regarding the LA, a test mass of  $5000 \pm 5 \text{ g}$  of particle size 10/14 mm was derived from the laboratory sample, and a total of eleven steel balls were gently added to the mass in the test drum. A test cycle completes at 500 revolutions, i.e., 15 min, and after the test, the aggregates were washed and sieved on a 1.6 mm sieve and dried. The mass loss (%) was then determined. For MD, a test mass of 500 g of size 10/14 was derived. Spherical balls amounting to 5000 g were gently added to the test mass plus  $2.5 \pm 0.5 \text{ L}$  of water in the cylindrical steel drum. One complete test cycle took about 2 h, and after the test, the aggregates were washed and sieved on a 1.6 mm sieve and dried. The average mass loss (%) of two test specimens were measured and calculated as the MD coefficient. These experiments were conducted at the laboratory of University of Agder (UiA) and the laboratory of the recycling site in Sandnes by Velde.

## 2.4. Chemical and mineralogical analysis

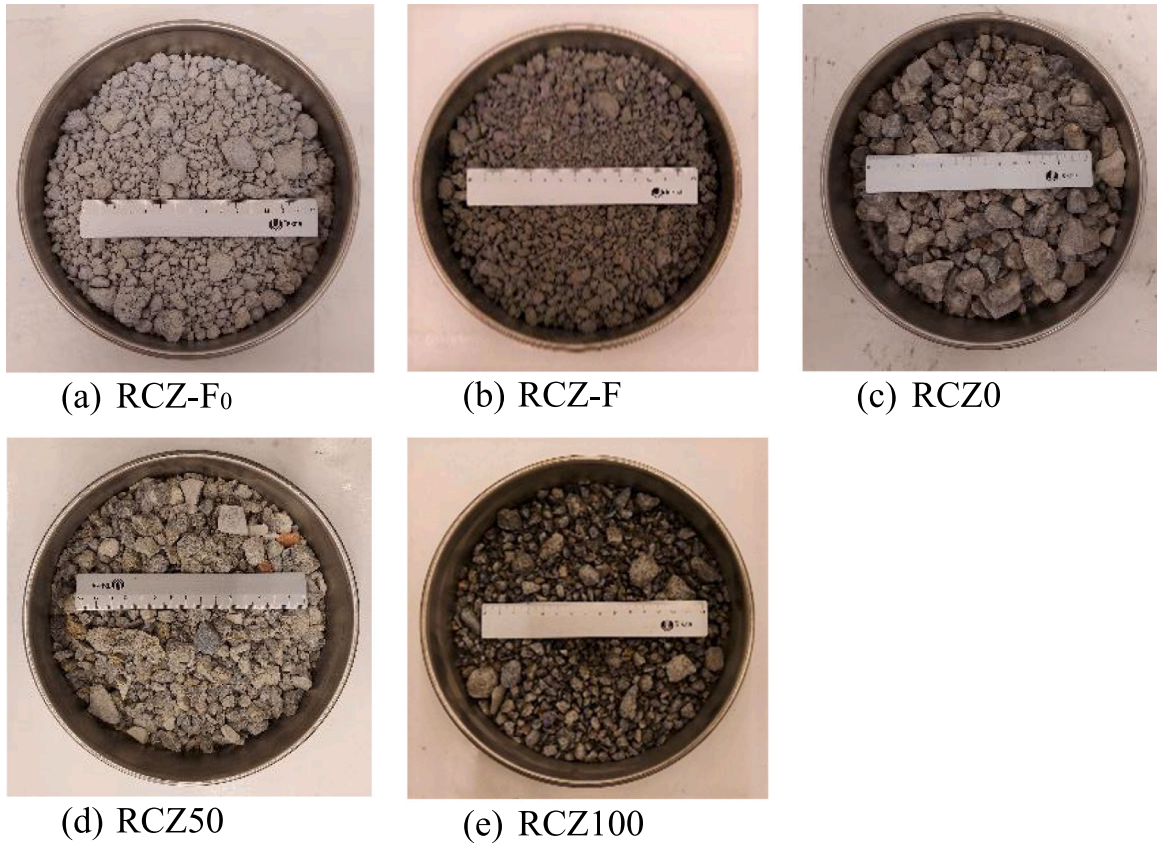
Determination of Al, As, Ca, Cd, Cr, Cu, Fe, K, Na, Ni, Mg, Mn, P, Pb, Si, Ti and Zn in the solid samples was conducted by inductively



**Fig. 1.** Production and sampling of recycled materials during full-scale pilot: (a) washing and sieving process (b) conveyor belt with recycled materials (c) direct sampling.

**Table 1**  
Samples collected with the mix ratio given in volume (%).

Sample	Wet processing	RCZ	EM
RCZ-F <sub>0</sub>	No	-	-
RCZ-F	No	-	-
RCZ0	Yes	0	100
RCZ50	Yes	50	50
RCZ100	Yes	100	0



**Fig. 2.** Materials used in the study: (a) RCZ-F<sub>0</sub>; Feedstock from raw feed pile, (b) RCZ-F; Feedstock stockpiled in open environment, (c) RCZ0; wet-processed (recycled) excavation materials, (d) RCZ50; 50% blends of wet processed (RCZ). (e) RCZ100; wet-processed (recycled) concrete sludge.

coupled plasma mass spectrometry (ICP-MS) according to ISO 17294–2 and EPA method 200.8. Analysis of Hg was done by Atomic Fluorescence Spectrometry (AFS) and Cr(VI) was analysed by ion chromatography with spectrophotometric detection according to ISO 15192:2010.

Acid solubility test was performed following the procedures described in NT Build 437. The acid solubility test comprised of samples milled and reduced to a test portion size. The test was performed on samples before and after the LA test. Fractions bearing the sample name RCZ-F<sub>0</sub>, RCZ-F, RCZ0, RCZ50, and RCZ100 were analyzed before LA. They were dried over night at 105 °C before they were pulverized in a disk mill (Siebtechnik, Labor-Scheibenswingmühle T.250). Fractions composed of RCZ0<sub>LA</sub>, RCZ50<sub>LA</sub> and RCZ100<sub>LA</sub> were received from < 1.6 mm after LA and therefore did not need further size reduction before drying. 4.0 ± 0.1 g of the sample were weighed (Mettler AE 260 Delta Range) directly in a beaker, the weight of the beaker had been determined with an accuracy of 1 \* 10<sup>-3</sup> g in advance. After this the samples were dried for 2 h at 105 °C before the weight was determined with an accuracy of 1 \* 10<sup>-3</sup> g. A large magnet was put into the glass before the addition of 3 mL absolute ethanol by use of pipette. Then 150 mL Type I water was added. The mix was then stirred by use of a magnet stirrer while 10 mL of HNO<sub>3</sub> was carefully added to the mixture using a pipette. The stirring continued for 10 min after the addition of HNO<sub>3</sub>. After the samples had settled for at least two hours or overnight, the samples were filtrated using a water suction apparatus and Ø 55 mm Whatman filter paper. Sand and fine particles that were not dissolved were transferred back to the beaker which were dried over night at 105 °C. Samples and beakers were then weighed again.

X-ray powder diffraction analysis was performed using a Bruker D8 Focus X-ray diffractometer in Bragg–Brentano geometry ( $\theta/\theta$ ) for the materials before and after removal of paste content by the wet technology. The samples were prepared by the back-loading

technique to minimize potential mineral orientation effects. Samples were scanned from 5 to 60 °2θ with Cu-Kα radiation, a step size of 0.2 °2θ and 0.8 s time per step. The diffractograms were qualitatively analyzed with EVA V4.3. Quantitative analysis was done by Rietveld refinement and profile fitting using TOPAS V.6, the ICDD PDF4 + and COD mineral structure databases. The Chebychev background model and sample displacement were refined. For the mineral structures, lattice parameters and scale were refined. Crystallite sizes were refined within reasonable limits. For mica, preferred orientation in (002) direction was additionally refined. In order to describe and quantify the mineral phases present in the materials, pulverized fragments obtained from < 1.6 mm sieve after LA was analyzed and compared with original samples. Hence, the minerals phases which shows the mineralogy of samples investigated is shown in Table 6. The results are normalized to 100% crystalline content. Uncertainty of the Rietveld results can be expected due to certain small amounts of non-carbonated X-ray amorphous C-S-H phases in the residual cement paste. However, the expected overall error of the quantitative analysis was expected to be in a similar range as the amount of potential X-ray amorphous hydration phases itself.

### 3. Results and discussion

#### 3.1. Physical properties

The particle-size distribution (PSD) of the materials investigated in this study is shown in Fig. 3. There was no significant difference between the PSD determined at UiA and Velde. However, the PSD of feedstock RCZ-F<sub>0</sub> and RCZ-F as determined at UiA varied. The cause of changes in the gradation of RCZ-F may be due to the effect of rainfall action and the storage time outside the recycling facility before sampled to UiA. In the case of Velde, RCZ-F<sub>0</sub> was not determined. The PSD of RCZ0, RCZ50 and RCZ100 was consistent with the 4/16 mm production line of the facility. Although RCZ100 was obtained from the same concrete sludge source, significant differences in textural characteristics resulting from efficient removal of poorly cured cement paste by intense washing and scrubbing unit of the recycling facility was observed (see Fig. 3).

The density and WA values as reported in Table 2 were obtained from the tests performed at UiA and Velde. In general, these parameters are influenced by the porous structure of mineral aggregates, hence they demonstrate the amount of water that can be absorbed. They are vital material properties required for road pavement and concrete production. The density results obtained from both test centers showed a similar trend. Reported values between the feedstock and recycled aggregates RCZ50 and RCZ100 did not significantly vary although poorly cured cement paste were removed from recycled aggregates during treatment. Nevertheless, it was observed that the density increased as RCZ content increased. Regarding RCZ0, Adomako et al., (2022) reported similar values in a study that investigated the mechanical performance of recycled aggregates derived from EM. Other studies have also reported the density for recycled aggregates obtained from ready mixed concrete waste within the range 1.65–2.72% [11,16,20,26]. It can also be mentioned that Norwegian rocks typically have a density within the range of 2.65–3.10 g/mL [16]. The values obtained for density clearly show that RCZ have similar density characteristics compared to other recycled and natural aggregates.

Unlike the density, significant differences were observed for WA, especially for the feedstocks. This observation may be due to differences in storage time at the recycling facility- Velde and UiA. Hence, the feedstock tested at UiA demonstrated high WA values. In this case, it may be suggested given the ambient storage conditions that the hardened and or dried nature of cement paste increased the pore structure [27]. Evidence of dry cement paste can be seen in Fig. 2. Regarding the feedstock at Velde, the low WA value may be related to the densification and refinement of microstructure of cement composites given its exposure to open environment and resulting carbonation [28]. It is well accepted in literature that carbonation treatment improves the WA of recycled aggregates from concrete waste [29]. The WA values for recycled aggregates at UiA were slightly higher than Velde. Generally, the WA of recycled aggregates from concrete waste are known to be high and this has a negative impact on overall performance. Low WA values recorded for processed materials indicate the effectiveness of the recycling technology on removal of loose components e.g., uncured cement paste.

For RCZ0, the WA obtained is higher than 0.3% reported for similar material in the study [30]. Studies that have investigated the performance of RCSA reported WA values within the margin 4–13% [20,22]. Given the variation of WA in RCSA, it is important to consider factors such as substitution level and water- cement ratio if used in concrete. [16,23]. Overall, the results demonstrated that RCZ have better quality performance.

**Table 2**  
Particle density and water absorption values of investigated materials.

Sample	Particle density (g/mL)		Water absorption (%)	
	UiA	Velde	UiA	Velde
RCZ-F <sub>0</sub>	2.68	2.64	7.62	3.10
RCZ-F	2.63	n.d. <sup>a</sup>	6.68	n.d. <sup>a</sup>
RCZ0	2.58	2.59	2.78	1.95
RCZ50	2.62	2.62	2.58	1.86
RCZ100	2.68	2.66	2.05	1.63

<sup>a</sup> Not determined

**Table 3**

LA and MD performance of the materials.

Sample	UiA		Velde	
	LA	MD	LA	MD
RCZ-F <sub>0</sub>	25	20	22	15
RCZ-F	23	18	n.d. <sup>a</sup>	n.d. <sup>a</sup>
RCZ0	24	12	26	10
RCZ50	22	10	24	11
RCZ100	18	11	20	11

<sup>a</sup> Not determined**Table 4**Acid soluble contents (wt%) in the samples with various particle size given as arithmetic mean  $\pm$  1 standard deviation, (n = 3) and (n = 4, LA).

Sample	Acid soluble part, %	Standard deviation,%	RSD, %
RCZ-F <sub>0</sub>	13.29	0.19	1.41
RCZ-F	13.80	0.05	0.35
RCZ0	4.58	0.18	3.96
RCZ50	8.27	0.41	4.96
RCZ100	7.14	0.07	0.93
RCZ0 <sub>LA</sub>	9.46	0.28	3.00
RCZ50 <sub>LA</sub>	12.04	0.28	2.34
RCZ100 <sub>LA</sub>	18.53	0.68	3.66

**Table 5**

Major oxide composition in the samples expressed in wt%.

Element	RCZ-AF <sub>0</sub>	RCZ-AF	RCZ 0	RCZ 50	RCZ 100	RCZ 0 <sub>LA</sub>	RCZ 50 <sub>LA</sub>	RCZ 100 <sub>LA</sub>
Al <sub>2</sub> O <sub>3</sub>	14.4	13.3	14.6	14.4	14.3	13.0	12.8	12.6
CaO	6.0	5.9	2.3	4.0	3.0	4.6	5.9	8.9
Fe <sub>2</sub> O <sub>3</sub>	4.6	4.8	2.9	4.3	4.9	2.3	2.8	3.2
K <sub>2</sub> O	3.4	3.4	3.9	3.3	3.3	3.8	3.6	3.6
MgO	1.0	1.0	0.6	0.9	1.0	0.6	0.7	0.9
MnO <sub>2</sub>	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.0
Na <sub>2</sub> O	2.9	2.8	3.8	3.2	3.2	2.7	2.6	2.5
P <sub>2</sub> O <sub>5</sub>	0.3	0.3	0.1	0.2	0.3	0.1	0.1	0.2
SiO <sub>2</sub>	70.8	64.8	74.5	70.8	68.2	74.6	71.2	65.8
SO <sub>3</sub>	0.3	0.3	0.1	0.2	0.2	0.2	0.3	0.5
TiO <sub>2</sub>	0.6	0.7	0.3	0.6	0.7	0.2	0.3	0.4
LOI- 1000° C	3.3	3.5	1.3	1.8	1.2	2.6	3.4	5.1

**Table 6**

Mineral phase contents (%) in the samples investigated in the study.

Mineral	RCZ-AF <sub>0</sub>	RCZ-AF	RCZ 0	RCZ 50	RCZ 100	RCZ 0 <sub>LA</sub>	RCZ 50 <sub>LA</sub>	RCZ 100 <sub>LA</sub>
Quartz	28.2	35.6	31.6	31.6	30.2	31.3	32.4	31.7
Feldspar	52.9	43.3	53.8	52.8	41.6	50.8	46.7	52.5
Calcite	4.8	5.1	1.6	1.4	10.9	2.4	3.9	1.9
Portlandite	0.5	0.3	0.0	0.1	1.7	0.4	1.2	0.4
Chlorite	0.4	0.5	2.2	1.6	0.9	3.3	3.3	0.4
Mica	8.4	6.5	5.9	5.9	6.3	6.3	5.2	8.6
Diopside	1.6	5.1	3.8	3.4	2.7	4.3	2.5	1.4
Clinker	3.2	3.6	1.1	3.2	5.7	1.2	4.8	3.1
Total	~100	~100	~100	~100	~100	~100	~100	~100

### 3.2. The Los Angeles and micro-Deval performance

The Los Angeles (LA) and micro-Deval (MD) test investigate the resistance to fragmentation and wear, respectively and are two most common tests used to analyze the performance of aggregates for concrete and in unbound applications. The results obtained for LA and MD are shown in Table 3. First, marginal differences in the performance can be seen in the results obtained from the two test sources. Considering the feedstock materials, the values obtained at UiA is slightly higher than Velde. It was observed in this case that the paste adhering to the surfaces of samples tested at UiA had severely disintegrated and this reflected in the sieving process as large

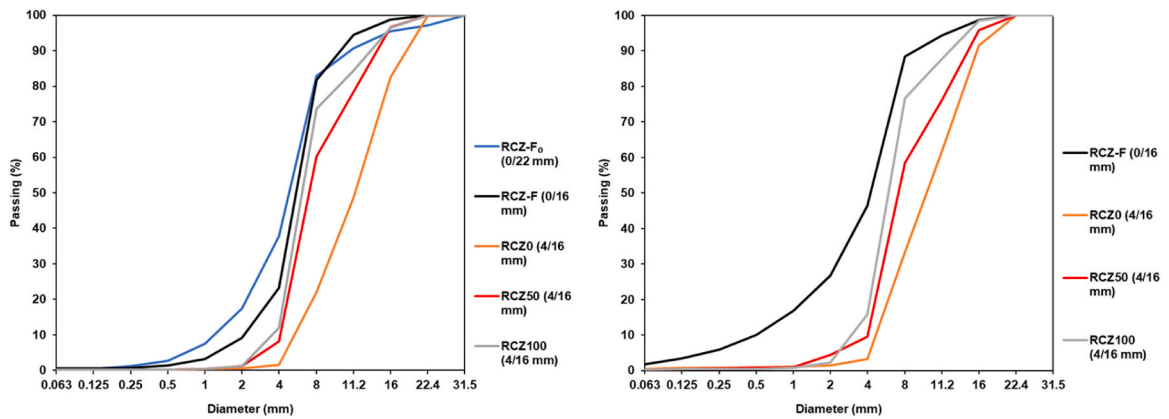


Fig. 3. PSD as determined at UiA (left), and Velde (right).

amount of  $< 1.6$  mm fractions contained such content. This resulted in increased mass loss when the LA coefficient was measured. This observation changed regarding processed materials as the values obtained at Velde were slightly higher. Overall, a clear trend in improved performance can be seen with increased RCZ. This was expected given that RCZ was composed of a significant amount of natural aggregates derived from concrete sludge. Secondly, this trend indicates that the developed admixture under proper curing conditions stabilizes the performance of recycled aggregates.

Regarding the LA for RCZO, other studies have reported stabilized results for excavation materials within the range of 24–28% [30, 31]. The LA for RCZ50 also show the optimal intermix of recycled aggregates RCZ and excavation materials. The positive effect of RCZ intermix can be explained by removal of weak paste (poorly cured). However, the results from acid solubility still revealed that RCZ100 contained a significant cement paste after wet treatment (see Section 3.3). Typical LA value for recycled aggregates from returned concrete waste has been reported to be 25% [16]. Generally, comparing the performance of materials investigated in this study to others e.g. recycled concrete aggregates, generic conclusion regarding the LA performance is that such materials have lower performance than natural aggregates. This is due to the crushing effect on residual mortar at the interfacial transition zone i.e., region of paste around aggregate particles [32,33]. For example, in a study that reported the LA of recycled concrete aggregates within the range of 35–42%, it was mentioned that the tendency to achieve less crushing resistance was due to increased amount of paste content [33]. Similarly, another study reported the LA of three different recycled concrete aggregates within the range of 38–41% [34].

The Norwegian road construction guideline report the LA limit criteria for natural aggregates for base at  $\leq 35\%$  [35]. Similarly, maximum LA values for different applications ranging from 30% to 50% are reported in the study [36]. Another study reported averaged LA values for eleven limestone, eleven marble and ten andesite rocks as 26%, 27% and 16%, respectively [37]. Based on these, it may be concluded that the performance of materials investigated is good and therefore they qualify to be used in unbound applications.

Regarding the MD results significant differences were seen in feedstock materials. Recycled materials demonstrated a consistent trend in both cases. This observation again confirmed the effect of the wet technique on removing weak paste on the interface of RCZ. The MD performance obtained in this study is significantly better compared to reported MD of 31% for recycled aggregates obtained from ready mixed concrete waste [16]. Slight differences in MD occurred for RCZ0. Nevertheless, they are consistent with reported MD values within the range 6–20% for excavation materials [31]. In Norway, a recent study proposed LA and MD criteria for intermix of recycled concrete aggregates and excavation materials of  $\leq 35\%$  and  $\leq 20\%$ , respectively [38]. These limit criteria were met by all materials investigated, especially RCZ50. In comparing the MD performance to recycled concrete aggregates, one study reported the MD within the region 28–30% [39]. The MD for natural aggregates i.e., basalt, granitoid and gabbroid rocks has been reported within the margin 8–9%. [40,41]. Another study have also reported the MD values for natural aggregates used in different applications within the range  $\leq 13$ –30% [42]. It is clear given these findings that RCZ advances the opportunity to increase the use of recycled materials from returned concrete waste under proper production and treatment.

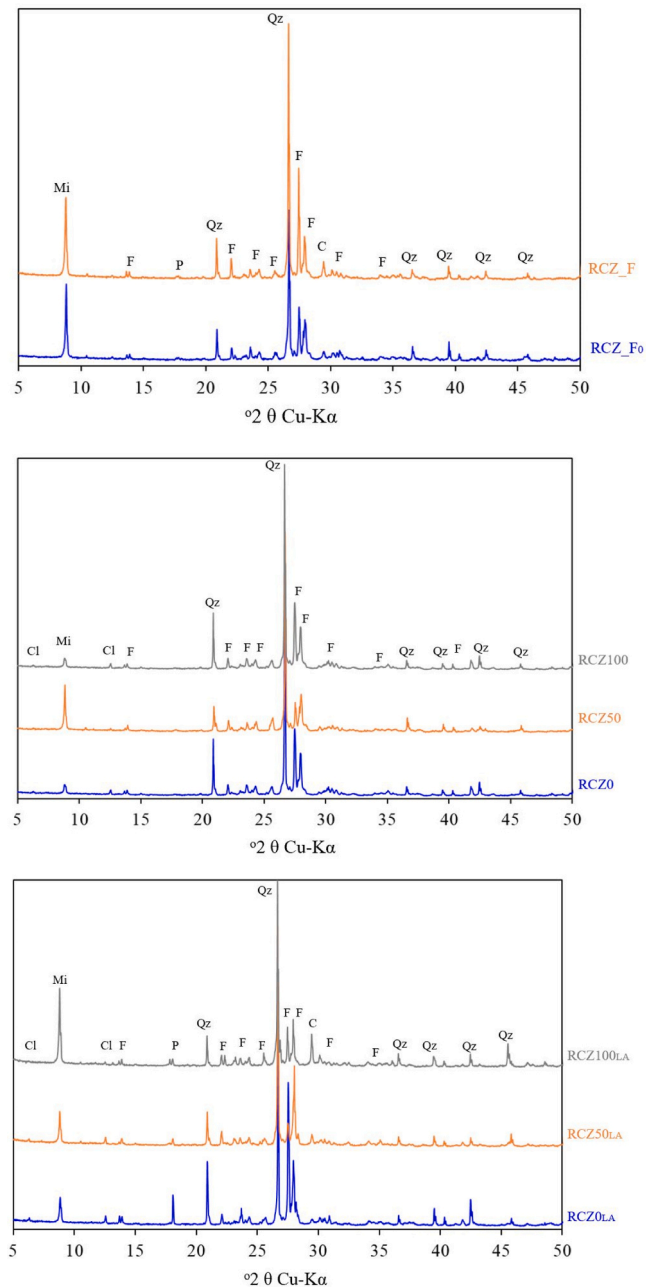
### 3.3. Acid soluble content and particle size

Acid solubility test were performed on samples obtained from UiA only and the results are reported in Table 4. The solubility rate of the feedstock were found to be the same. Similar observation was realized in RCZ50 and RCZ100 whereas RCZ0 was the main insoluble material given a 5% soluble part. Generally, the results followed a consistent pattern in relation to the LA performance. By this, RCZ-F<sub>0</sub>, and RCZ-F which recorded LA of 25% and 23%, respectively were shown to be highly soluble. This was not surprising given the source and the fact that both feedstocks did not receive wet treatment, subsequently indicating more amount of cement paste. Recycled RCZ50 and RCZ100 demonstrated low amount of paste content which also reflected in the LA values of 22% and 18%, respectively. Further, this confirmed the removal of loose paste content by applied treatment and maximizes the benefits of producing recycled aggregates RCZ and excavation materials. The relation that high paste content reduces the LA performance has been demonstrated in some studies [33,43].

Samples denoted  $_{LA}$  were obtained from  $< 1.6$  mm sieve after LA.  $RCZO_{LA}$ ,  $RCZ50_{LA}$  and  $RCZ100_{LA}$  showed increased solubility rate which means the paste content was more profound in small particle size fractions. This trend can be seen by the increased solubility for  $< 1.6$  mm samples by increased RCZ content. Generally, the relation that acid soluble content increases as the particle size reduces is consistent with the findings reported earlier [44]. In view of this, it is feasible to expect that the fine fraction will contain a higher amount of cement paste than the coarse fraction of recycled materials at the production facility. In the case of increased solubility for  $RCZO_{LA}$  the reason may be due to the presence of residual paste from  $RCZ50_{LA}$  and  $RCZ100_{LA}$  since all materials were tested in the same machine.

### 3.4. Oxide composition and change in mineralogy

The results for oxide and heavy metal composition are reported in Table 5 and Table 6, respectively. Regarding the major oxides,



**Fig. 4.** X-ray diffractograms pattern of samples investigated and marked with the prominent peaks of the main mineral phases Mi = Mica, F = feldspar, Qz = Quartz, C = Calcite, P = Portlandite, Cl = Chlorite.



slight differences were observed between the materials. The content of CaO found in the feedstock was higher than recycled materials. Again, this observation means that some of the paste were removed during the wet process. A clear trend of increased CaO content was found in the fine fraction of RCZ samples after LA which supports that paste content is susceptible to crushing. In addition, these findings were in accordance with the trend observed in the acid soluble results as demonstrated in Table 4. This again supports the theory that some of the paste is removed during the wet process. Some studies show that the major element oxides are influential factors given their effect on durability, hardness, toughness, and soundness properties [40,45]. The most apparent element is SiO<sub>2</sub> as expected due to the mineralogy (discussed below). It can be observed that SiO<sub>2</sub> content decreases with increasing RCZ because more properly cured cement paste is introduced.

The quantified mineral phases in both original and pulverized residues (<1.6 mm) are shown in Table 6. The dominant minerals identified were typical for Norwegian aggregates, i.e. feldspar, quartz, phyllosilicates (mica and chlorite) and minor amounts of pyroxene (diopside). The main feldspar minerals identified were albite, while anorthite, microcline and orthoclase was also found. In addition, paste minerals like portlandite and residual clinker phases were identified besides calcite. The clinker minerals were mainly larnite (Ca<sub>2</sub>SiO<sub>4</sub>) and brownmillerite (Ca<sub>2</sub>(Al,Fe)<sub>2</sub>O<sub>5</sub>). The results are normalized to 100% crystalline phase content. The discrepancy between the acid soluble amount and the paste phases detected is probably due to the X-ray amorphous phases of calcium silicate hydrate which were not considered here. Some differences in mineral content were observed between the samples before and after LA. Considering calcite, RCZ100 recorded the highest amount but there was a significant reduction in RCZ100<sub>LA</sub>. Other recycled materials RCZ0 and RCZ50 recorded lower concentrations but slightly increased amounts were observed in RCZ0<sub>LA</sub> and RCZ50<sub>LA</sub>. All samples reported a low amount of Portlandites. The clinker phases were not marked in the figures. This was because of peak overlap with other main minerals and low overall intensities in comparison to feldspar and quartz. Note that the presence of mechanically weak minerals e.g., Chlorite is slightly higher in RCZ0 and RCZ50, and RCZ0<sub>LA</sub> and RCZ50<sub>LA</sub>. This is because the excavation materials used in the study is originally characterized by different geological make up i.e., phyllites [30]. Nevertheless, the content of mica is consistent and present in all samples. Generally, these primary minerals identified as quartz, phyllosilicates, and feldspar, are known to influence the mechanical performance of rocks, [30,36,46,47]. Unlike quartz and feldspar which contributes to performance improvement, phyllosilicates are mechanically weak minerals. However, in this study, the content of mica and chlorite as found in excavation materials did not compromise overall mechanical performance. This phenomenon is not only attributed to the content but also the disposition through distribution and structural formation of the grain boundaries [47]. Hence, the LA reported for excavation materials as 24% and 26% from both test centers are equivalent to the LA of some rocks (e.g., Arkose, Granite, Pegmatite) found in Norway [42]. Fig. 4.

### 3.5. Chemical species of potential concern (COPC)

The environmental applicability of RCZ was screened by assessing the COPC level in the feedstock and new aggregates. In addition, the LA fine samples (< 1.6 mm) were included to disclose any increased concentrations in the weak mineral part of the RCZ. Furthermore, Norwegian content limits for concrete waste, that recently have been developed by Norwegian Environmental Agency (NEA) were used to evaluate the COPC level [48]. They were derived from risk assessments based on COPC leaching evaluation and Norwegian soil quality limits [49]. Concrete and masonry waste that comply with these limits can be used without calculating the environmental risk in case-by-case for recycling scenarios above groundwater level and not submerged in water (e.g. sub-base in road construction). The limits are often used as first-stage evaluation of waste-derived binders and recycled aggregates used for concrete, since the unbound recycling scenarios (granular condition) are more critical for unacceptable release of COPC than the use in concrete (monolithic condition). Hence, compliance with the Norwegian NEA limits ensures limited spreading of COPC to the environment in the practical recycling application scenarios [48]. The results are shown in Table 7 and the concentrations were found to be low with some exceptions, i.e., elevated concentrations for Cu, Cr and Zn were found in the washed RCZ which exceeded the NEA limits. If the RCZ0 (washed excavation materials) are compared to the concrete sludge feedstocks RCZ-AF<sub>0</sub> and RCZ-AF, it can be observed that the elevated levels originated from the excavation feedstock. In addition, these levels decrease significantly as concrete sludge content was introduced in the recycling process.

Furthermore, under oxidised conditions hexavalent Cr (CrO<sub>4</sub><sup>2-</sup>) may form, which in earlier studies has been identified experimentally [50] and by geochemical speciation modelling [51] as bound in ettringite solid solution in recycled concrete aggregates. In the present study, the Cr(VI) level was low in RCZ samples (see Table 7) which will ensure low leaching of Cr upon carbonation and a decrease in pH. Moreover, all Cr(VI) values were below the Norwegian soil quality criteria of 2 mg/kg [49]. It can also be seen that the wet recycling process decreased the Cr(VI) level when the feedstock and RCZ100 are compared. It can be noted that the recycling facility has full treatment of polluted water and the removal of Cr(VI) in the present process may be found to be a viable solution.

If the fine fractions (<1.6 mm) are examined, a significant concentration increase was only found for Zn and Cu when the concrete sludge feedstock increased. The cement paste content also increased in the fine fractions upon increased sludge content (shown in Table 4), which explained the elevated concentrations in RCZ100. However, the COPC levels in the fine fractions were low which is promising regarding potential impact on soil and groundwater, since the cement paste is the most chemically active part regarding the release from recycled aggregates.

## 4. Conclusions

This paper investigates the technical and environmental properties of Re-Con Zero dry washing technology used to produce recycled aggregates from concrete sludge (RCZ) and combined as a feedstock in wet recycling excavation materials. The production followed sample classification RCZ0, RCZ50 and RCZ100 within the range 0–100%. The Los Angeles (LA) and micro-Deval (MD)

**Table 7**

Content of COPC in the materials compared to Norwegian criteria for concrete waste. Concentrations are given in mg/kg.

Element	RCZ-AF <sub>0</sub>	RCZ-AF	RCZ 0	RCZ 50	RCZ 100	RCZ 0 <sub>LA</sub>	RCZ 50 <sub>LA</sub>	RCZ 100 <sub>LA</sub>	NEA limit <sup>a</sup>
As	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	15
Cd	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1.5
Cr	131	105	168	139	107	30.2	24.8	32.7	100
Cr <sup>6+</sup>	0.8	0.7	< 0.3	< 0.3	< 0.3	1.4	1.4	1.9	8
Cu	49	47.5	206	33.4	29	38.5	36.8	49.4	100
Hg	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	1
Ni	11.7	12.9	10.4	8.3	7.4	8.3	10.9	9.4	75
Pb	28.5	27.7	35.9	25.8	23.3	32.9	33.8	29.6	60
Zn	96.5	99	250	72.6	87.1	49	56.7	70.7	200

<sup>a</sup> Waste regulation limits for concrete waste developed and issued by Norwegian Environmental Agency (NEA, 2022)

performance demonstrated RCZ to be a good material and therefore increasing the amount of RCZ enhanced the performance of final product. This observation was clearly visible in reported LA and MD values. X-ray diffraction analysis performed on original and pulverized residues (< 1.6 mm) identified dominant mineral phases to be feldspar, quartz, phyllosilicates (mica and chlorite) and minor amounts of pyroxene (diopside). Furthermore, some differences in paste mineral (calcite) were observed, e.g., while a significant amount was found in RCZ100, the amount in RCZ100<sub>LA</sub> significantly reduced. Conversely, low concentrations were reported for RCZ0 and RCZ50 with a marginal increase in RCZ0<sub>LA</sub> and RCZ50<sub>LA</sub>. Regarding the acid solubility, the study showed that paste content in particle sizes (<1.6 mm) obtained after LA test was significantly higher than in the coarse fractions. This phenomenon confirmed the presence of paste in RCZ after wet treatment although the treatment process removed poorly cured paste. The contents of chemical species of potential concern (COPC) were found to be low and mostly complying to Norwegian environmental criteria. It was also found that Cr(VI) was not detected in wet treated RCZ and strongly indicate low leaching of Cr upon carbonation and a decrease in pH. Hence, the results were promising and can be used for further development of separate RCZ and in combination with excavation materials. The approach may increase the extended use of both materials and offer significant technical and environmental benefits.

### Declaration of Competing Interest

The authors declare no conflicts of interest.

### Data Availability

Data will be made available on request.

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