

# Toward Carbon-neutral Concrete: Early Age Strength of Mechanically Activated Construction and Demolition Waste-based Binders

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## Abstract

There is need to research and develop sustainable building materials from waste and by-products with adequate standards for increasing infrastructural and environmental need occasioned by population increase, modernization, urbanization, environmental and climatic changes concern currently. In unprocessed form it is not possible to up-cycle concrete waste, therefore mechanical activation (MA) technique can be applied to up-cycle waste, through improvement of properties for secondary raw materials.

This study focuses on effect of early age compressive strength and MA of construction and demolition waste (CDW) hence advocacy for carbon neutral concrete.

MA improved the early age strengths of CDW based binder strengths. The finer CDW samples had better strength at 7 days compared to coarser. Generally, reduction of water to binder (w/b) ratio resulted to higher pozzolanic activity index for binders with 25% CDW. The 25% cement replacement with MA CDW as binder replacement was optimum, with highest respective compressive strengths of  $67.02 \pm 1.56$  MPa and  $62.82 \pm 12.15$  MPa, for ranges 5303–8440 cm<sup>2</sup>/g (average 6872 cm<sup>2</sup>/g) and 12,102–10,327 cm<sup>2</sup>/g (average 11214 cm<sup>2</sup>/g) geometric specific surface areas based CDW's binders respectively.

Remarkable strength for MA of CDW could be due to a combination of impact of Si reactivity and filler effect in the CDW. Water content, particle sizes and carbonation had an impact on compressive strengths for binder materials. Inconsistency in particle sizes from different batches was possibly due to the quartz amount.

## Keywords

mechanical activation, construction and demolition waste, binder, compressive strengths

## 1 Introduction

There is need to research and develop sustainable building materials with adequate standards for increasing infrastructural and environmental need occasioned by population increase, modernization, urbanization, environmental and climatic changes concerns currently. In unprocessed form it is not possible to up-cycle waste/by-products, therefore MA technique is applied to up-cycle waste. Particle size and structural change due to MA improves the physical and mechanical properties of material and resultant concrete and cementitious products, for construction materials. MA can be utilized to improve the properties of mineral material, hence improving the up-cycled value.

The merits of using MA for improvement of bulk and surface reactivity is well accepted [1]. However, smaller size particles make grinding significantly harder to reduce individual sizes further. Construction and demolition waste and glass in particular may require longer milling times hence more energy-ineffective, time consuming and costly [2]. Increment of grinding time can increase grinding efficiency, but increases energy consumption [3]. Also, the equipment and experiment set-up affects the material product. Fediuk [4] showed that grinding the planetary mill grinding had higher specific surface areas as compared to vibration and ball mill, with ball mill being the least. It is important to determine optimum conditions for grinding

that will achieve sufficient material properties, while optimizing the input. Grinding beyond optimum specific surface area for composite cementations binder had negative impact on the structure, due to increased activity that speeds the setting time and inhibits the forming of spherical particles uniform distribution in the micro-structure [4]. Mucsi et al. [5] investigated on construction and demolition waste (CDW) powder, particles size and specific surface area ground by stirred media, the increase after 5 min grinding was attributed to coating of grinding balls due to aggregation of extra fine CDW particles also at higher grinding times, this study showed attributes of increment of activated surface and agglomeration.

Models for prediction of aggregate concrete or binder properties, incorporated with waste/by-product, either as binders or aggregate have been conducted previously. Amar et al. [6] evaluated the compressive strengths prediction incorporated with assorted wastes was  $R^2 > 0.95$ , test. Getahun et al. [7] investigated on including rice husk ash based partial binder and reclaimed asphalt concrete based partial aggregates, the selected model had regressions  $> 0.98$ , for strengths prediction.

Mucsi et al. [5] showed that improved strength of the 28 days strengths of binders based on milled concrete CDW- up to 30%- attributed to CDW mineralogy from fine aggregates and other minerals that are unreactive, those hard minerals contribute to strength improvement, also with high-energy-intensity grinding, milling revealed the closed pores onto which surfaces reactions can be effected. Moreno-Juez et al. [8] reported that for up to 10% concrete CDW binder, no significant change of the 28 and 90 days compressive strengths compared with based binder, with declines of just  $< 10\%$ . Petrov and Zaharieva [9] showed that the curing type had an significant impact on waste concrete-based binder, with moisture curing optimum at 28 days and significantly resulted to reduced strengths declines between 7 and 28 days for up to 45% waste concrete based samples compared with the cement samples. Mao et al. [10] showed that, within China, incorporation of concrete-CDW resulted to reducing compressive strengths with increasing CDW content, at 3, 7 and 28 days, also the costs and  $\text{CO}_2$  emission ( $\text{kgCO}_2\text{-eq/m}^3$ ) reduced, reaching to  $> 40\%$   $\text{CO}_2$  emissions for 60% brick/concrete CDW admixtures based composites in 4 regions. Kancheva and Zaharieva [11] showed that incorporation of 5–30% waste concrete powder, as compared with  $> 90\%$  clinker cement, had lower global warming potential, Ozone depletion potential, acidification potential and abiotic resources. The study of Luo et al. [12] showed that

the total  $\text{CO}_2$  emission for recycled cement was 0.043 tons  $\text{CO}_2$ /ton of recycled cement, compared with 0.66 tons  $\text{CO}_2$ /tons for Portland cement cited from Li et al. [13], a reduction of 93%, in China.

This study focuses on early age strength of MA construction and demolition waste (CDW) based binder for carbon neutral concrete production possibilities.

## 2 Materials and methods

### 2.1 Materials

The CDW waste derived from sieving  $< 4$  mm of concrete waste, after the jaw crushing of larger fractions [14], with particle sizes of CDW and cement (CEM I) illustrated in Fig. 1. Portland cement type 1 (CEM I) 52.5-SR O/NA, with chemical composition in Table 1 and tap water were utilized. Chemical composition from X-ray fluorescence (XRF) analysis is given in Table 1, showing

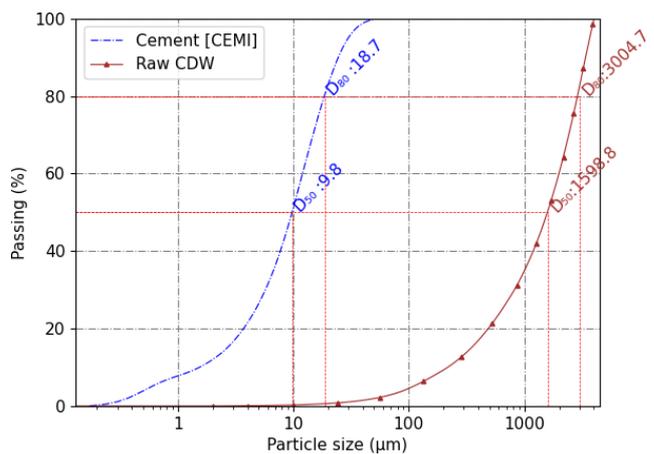


Fig. 1 Particle size distribution for cement (CEM I) and raw CDW

Table 1 X-ray fluorescence (XRF) analysis for CDW [14] and Portland cement type 1 (CEM I), normalized

Composition	CDW (%)	Cement (%)
$\text{SiO}_2$	52.97	28.11
$\text{Al}_2\text{O}_3$	5.79	2.76
$\text{MgO}$	1.25	1.38
$\text{CaO}$	20.73	54.78
$\text{Na}_2\text{O}$	0.61	0.19
$\text{K}_2\text{O}$	1.43	0.29
$\text{Fe}_2\text{O}_3$	1.61	3.67
$\text{MnO}$	0.10	0.24
$\text{TiO}_2$	0.19	0.11
$\text{P}_2\text{O}_5$	0.09	0.17
S	0.81	4.85
F	$< 0.3$	$< 0.3$
Loss on ignition (LOI)	14.34	3.25
Others	0.078	0.19
Total	100	100

an CDW's acidic oxides ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ) at 60.68%, significantly higher than CEM I.

## 2.2 Methods

### 2.2.1 Mechanical activation and geometric specific surface areas

MA through grinding in a batched process was conducted by Retsch type planetary mill. The mill has four grinding bowls, with internal dimensions of  $\text{Ø}100$  mm and 70 mm height, radius to the bowl's centers is 150 mm. The grinding media included  $\text{Ø}40$  mm steel balls, three pieces for each bowl. Speed was 128 revolutions per minute with materials to grinding media ratio of 1:10 by mass. The raw and ground CDW were used for grinding times (minutes): 3, 5, 10, 15, 30, 60 and 120. Maroof et al. [15] presented a historical review on different shape coefficient/factors for soils and powders that relate with the specific surface area, including the Heywood shape factor, and from previous research a factor of 1.5 was multiplied to the geometric specific surface areas derived for sphere shape particles, for all in this study. This factor aligns well with the study of Maroof et al. [15].

### 2.2.2 Compressive strengths and densities

The 25% CDW cement replacement specimens, with 0.5 and 0.3 water to binder (w/b) mass ratio were prepared for compressive strength. Also, strength was conducted with the two finer precursors CDW at 0.3 w/b, by mass, with varying CDW binder amount i.e., 0, 25, 50 and 100% mass ratios. The two selections were conducted based on the previous results of pozzolanic reactivity, highest for the 2nd finest precursor [16], and the preceding test results from this study (0.5 w/b samples).

Bulk densities were recorded before crushing the samples. Cube shape molds with size of 20 mm were used for compressive tests. Three specimen series were cured and tested for early age strength (at day 7) compressive strengths. The 7-days strength development or monitoring is usually practiced, and standards for binder/concrete/mortar such as SIST EN 197-1:2011 [17] and ACI 318-19(22) [18] standards.

In this study, the relationship between the CDW binder and pure cement binder was used as an indicative binder's pozzolanic activity index, calculated in Eq. (1) and computed and evaluated based on strength activity index of 75% adopted from ASTM C618-25a [19] standard value, for fly ash or natural pozzolanic materials, percentages and strengths durations were customized for this study:

$$\text{Pozzolanic activity index} = \frac{\sigma_x}{\sigma_{\text{cement}}} \times 100\%. \quad (1)$$

where:

- $\sigma_x$ : compressive strength sample with cement replacement;
- $\sigma_{\text{cement}}$ : compressive strength of cement sample.

Regression models/equations, using python 3 were developed, from LibreCalc [20] dataset. The calculated geometric specific surface areas (SSA) against compressive strength at day 7 graph  $R^2$  (square of Pearson product moment correlation co-efficient) were calculated, for a validation dataset with 5 of the 8 datasets (62.5%), after randomization process in LibreCalc [20] and also entire dataset.

### 2.2.3 Mini-slump cone test

Mini-slump cone test was conducted using a truncated cone mold with the sizes of  $\text{Ø}40$  mm and  $\text{Ø}20$  mm at the bottom and top respectively and a height of 56.5 mm. This miniature test is a downsized Abrams cone geometry (Kantro [21]; Tan et al. [22]). However, for this study, majority of the samples no significant flow occurred, even at 0.5 w/b, so the study measured the heights of mini-slump, instead of the diameters. Kantro [21] used the areas, however for this study, the wet mix was placed and compacted in the mold. The mold was then removed and the difference between the height of the mold and that of the sample were recorded for comparison of workability.

### 2.2.4 FTIR analysis

The chemical bonds were investigated by Fourier-transform infrared spectroscopy (FTIR) analysis using a JASCO FT/IR 4220 spectrometer in reflection mode, with diamond ATR PRO470-H accessory [23]. 32 scans between  $4000 \text{ cm}^{-1}$  and  $400 \text{ cm}^{-1}$  were averaged with each spectrum at  $0.964 \text{ cm}^{-1}$  increment, each spectrum is an average of the results of three runs [23].

## 3 Results and discussion

### 3.1 Mechanical activation and materials

The CDW material was from various sizes of concrete waste [14]. The CDW mechanical activation was a batch system. In practice and as observed variations between batches occur for the same equipment parameters. Particle size distribution for mechanically activated CDW was measured from more than one batch, to improve the accuracy for the representative grinding time, with the exception of MA CDW<sub>60</sub>, having a 59% variation, all others had < 20%. Table 2, denotes the parameters for grinding duration, SSA and codes for this study, related with MA duration i.e., MA CDW<sub>x</sub> represents CDW with x minutes of MA.

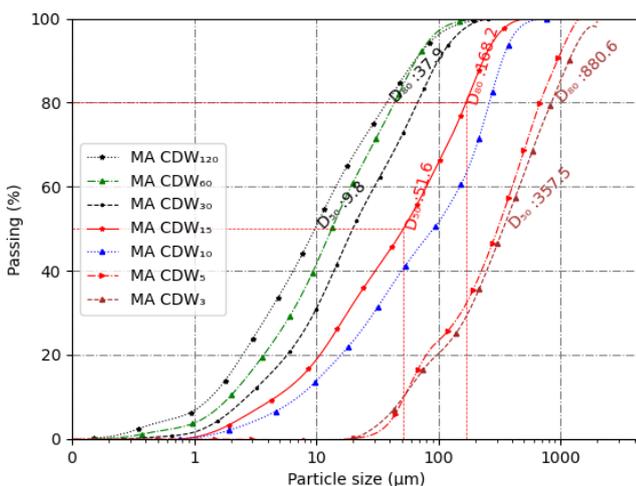
**Table 2** Geometric specific surfaces for varying CDW grinding times

Grinding time (min)	Geometric specific surface area (cm <sup>2</sup> /g)	Average (cm <sup>2</sup> /g)	Denote
3	153–182	169.28	MA CDW <sub>3</sub>
5	225–246	240.48	MA CDW <sub>5</sub>
10	2196–1898.92	2047.53	MA CDW <sub>10</sub>
15	2634–3042	2838.09	MA CDW <sub>15</sub>
30	4583–5203	4892.9	MA CDW <sub>30</sub>
60	5303–8440	6871.53	MA CDW <sub>60</sub>
120	12102–10327	11214.34	MA CDW <sub>120</sub>

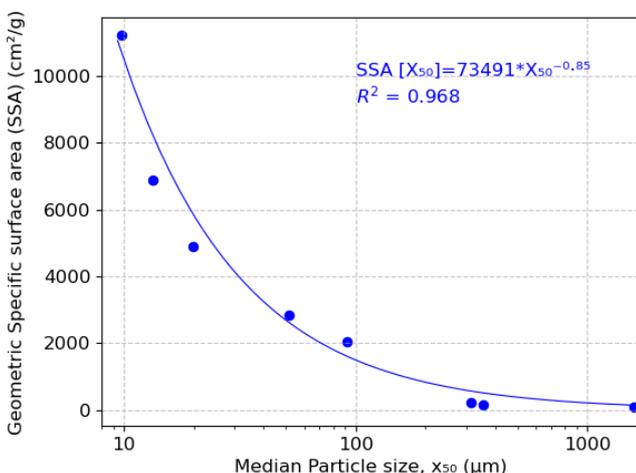
Fig. 2 is the representation of particle size distribution curves, the median size ( $D_{50}$ ) reduced to around 10  $\mu\text{m}$  after grinding.

Fig. 3 is the representation of particle size distribution curves and SSA, with a strong fit  $R^2 = 0.968$  between the particle size and SSA, for a power function.

Table 3 shows the X-ray diffraction (XRD) for MA CDW<sub>60</sub>, showing significant quartz in the sample, and only 13.7% amorphous phase. Also after mechanical



**Fig. 2** Particle size distribution curves for crushed and ground MA CDW



**Fig. 3** Geometric Specific surface areas for crushed and ground MA CDW

**Table 3** X-ray diffraction (XRD) analysis for MA CDW<sub>60</sub>

Minerology	%
Quartz	63.66
Calcite	10.81
Dolomite	0.22
Andesine An50	7.8
Muscovite 2M1	1.55
Orthoclase	2.25
Amorphous	13.7

activation, the XRF for MA CDW<sub>60</sub> changed with notable increase in SiO<sub>2</sub> to 66.27% and decrease in CaO<sub>2</sub> to 14.72% and LOI to 9.74%.

Inconsistency in particle sizes contributed to variations in SSA, Table 2, from different batches. Szabó et al. [24] found out that there was no correlation of cement stone CDW grinding time and resultant compressive strengths at various replacement levels. This was attributed to heterogeneous nature of recycled concrete [8, 24, 25] also the quartz content [24], similarly, based on reviews and Table 3 for MA CDW<sub>60</sub>, the inconsistencies for this study was possibly due to high quartz, and heterogeneous CDW.

The particle size distribution decreased while the specific surface areas for the crushed and ground materials increased with increasing grinding. Comparison between MA CDW<sub>120</sub> and MA CDW<sub>60</sub> based samples, the SSA increased by 76.2% and particle sizes ( $D_{50}$ ) reduced only by 26.8% respectively. High quartz content in CDW, from sand, hinder efficient grinding [24], hence the lower decrease rate for particle size could be due to significant amounts of hard-to-grind quartz, i.e., Table 3.

Table 1, the amount of Al<sub>2</sub>O<sub>3</sub> was higher in CDW compared with cement's, the same was not expected to change significantly after MA. Thomas et al. [26] found out that the amount of available alumina content in supplementary cementitious material, more significant at a 0.5 water to cement ratio, increased the chloride binding capacity of result binders. Hence, the amount of available alumina, could have a positive effect of increased chloride binding hence lower chloride penetration. The loss on ignition (LOI) for raw CDW was 14.34%, but it was realized that after > 15 min MA, the same reduced in the range of 10%. This suggests that MA can reduce durability issues for resultant concrete, with reduced LOI.

### 3.2 Compressive strength and densities

#### 3.2.1 MA of CDW and water content

The early age strength (at day 7) compressive strengths for 0.5 w/b binder are illustrated in Fig. 4, the cement binder reference sample had a strength of  $26.82 \pm 0.94$  MPa,

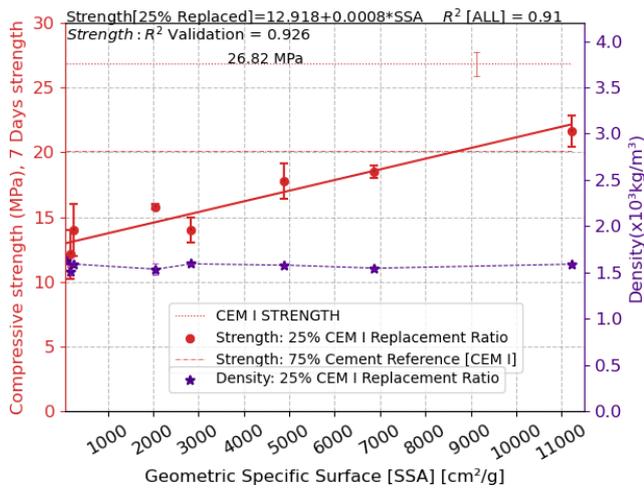


Fig. 4 The 7 day – compressive strengths and densities for 0.5 w/b for 25% CEM I replacement with MA CDW

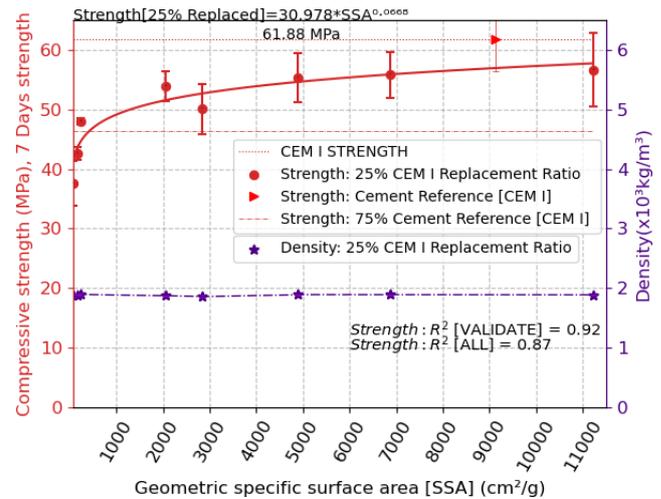


Fig. 5 The 7 day – compressive strengths and bulk densities for 0.3 w/b for 25% CEM I replacement with CDW

the MA CDW<sub>120</sub> based mixed had  $21.62 \pm 1.22$  MPa. No clear correlation between the bulk densities and the 7-days strengths, could be an indicator of various factors, with differing impacts such as porosity, water demand and bulkiness of heavier and bigger particles.

Generally, increase in MA improved the compressive strengths, with the 25% MA CDW<sub>120</sub> based sample attained 81% pozzolanic activity index, the rest were < 0.75%. The MA CDW<sub>120</sub> had almost the same volume for < 1 μm, higher < 5 μm and almost similar D<sub>50</sub> particles compared with cement, that possibly acted as fillers and contributed to strength development. Reduced strength for coarser MA CDW could be due to reduced reactive ingredients and insufficient fillers for strength development. Finer particles of MA CDW can fill voids between cement particles and MA CDW, hence contributing to high strength activity index, due to concrete powder's pozzolanic reaction with Ca(OH)<sub>2</sub>, hence increased calcium silicate hydrate (C-S-H), CDW powder with high amount of particles < 1 μm and high reactive specific surface area, promotes reaction and bond particles [5]. The portlandite reacts with reactive silica hence development of secondary C-S-H, thermal and mechanical activation of waste concrete powder allows more silicate and reactive silica for reaction with lime, and development of higher compressive strengths [27]. At higher grinding times, increased C-S-H is an indication of possible amorphization, also increase in calcite and other carbonates with increased fineness [24]. Fig. 5 are the strengths at day 7 for 0.3 w/b ratios. The MA CDW<sub>120</sub> based binder, for 7 days strength had a compressive strength of  $56.66 \pm 6.15$  MPa, with pozzolanic activity index of 92% the highest for respective series. Generally, a reduction of bulk densities with increased CDW grinding occurs.

This improvement can be attributed to lower water demand by CDW, particularly the MA coarser based samples. Excessive water at 0.5 w/b ratio possibly resulted to higher porosity of hardened concrete, after evaporation of excess water, hence reduction of strengths for the CDW incorporated specimen.

Sánchez de Rojas et al. [28] showed that heat of hydration differed with different additives to cement, over time, additive material continues to have an important role. This could have some beneficial or adverse effect (shrinking or microcracks) on binder matrix [8]. The 7-day samples at 0.5 w/b ratio generally exhibited lower compressive strengths compared with the reference, Monasterio et al. [25] and Kim and Choi [29] showed had a similar trend. The reduction in strength could be due to granite [30], slate [31]. Monasterio et al. [25] showed that the cement-based mix had highest strength and lowest accessible porosity at 28-days and generally the calcareous aggregates waste powder-based mixes had higher accessible porosities and lower strengths compared with the siliceous aggregates waste mixes. Vashistha et al. [27] showed that generally, the samples with higher porosity had lower compressive strengths. Zhao et al. [32] showed that a combination of secondary hydraulic reaction of waste clay brick powder and cement hydraulic reaction, would result in a reduction in total porosity and optimization of pore structure, also the porosities decreased as sizes of powder decreased.

Smaller particle size promotes early age strength development, due to more reaction [5]. The probability of more active SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in waste clay brick powder, that reacts with CH after 28 days resulting to more C-A-H and C-A-S-H, that could bind other hydration products [33].

The strengths for 0.3 and 0.5 w/b had  $R^2$  of 92% and 92.6% respectively between the compressive strength and geometric specific surfaces areas, for the validation dataset, for the entire dataset the 0.3 and 0.5 w/b had  $R^2$  of 87% and 91% respectively. The relationship compressive strengths and SSA for fitting curves in Figs. 4 and 5 are presented in Eqs. (2) and (3) respectively:

$$\text{Strength}(0.5_{w/b}) = 12.9185 + 0.0008 \text{ SSA}, \quad (2)$$

$$\text{Strength}(0.3_{w/b}) = 30.978 \text{ SSA}^{0.067}. \quad (3)$$

In Eq. (2):

- unit strengths are in MPa;
- SSA is in  $\text{cm}^2/\text{g}$ ;
- coefficients are in MPa,  $\text{N} \times \text{kg} \times 10^{-5}/\text{mm}^4$ .

In Eq. (3):

- unit strengths are in MPa;
- coefficient is in MPa  $[\text{cm}^2/\text{g}]^{0.067}$ .

### 3.2.2 Effect of CDW content and consistency

The finer MA CDW samples were tested, including fresh samples for 25% MA CDW and CEM I based samples, for varying CDW content as cement replacement. Fig. 6 shows the early age (at day 7) compressive strengths, with the 25% cement replacements and 0.3 w/b, MA CDW<sub>60</sub> and MA CDW<sub>120</sub> replacements had strengths of  $67.02 \pm 1.56$  MPa and  $62.82 \pm 12.15$  MPa which were 12% and 5% above respective cement binder strengths.

The 2 degree polynomial equation for strengths' fitting curves in Fig. 6 are presented in Eqs. (4) and (5) as:

$$A = -0.00645X^2 - 0.067X + 68.03, \quad (4)$$

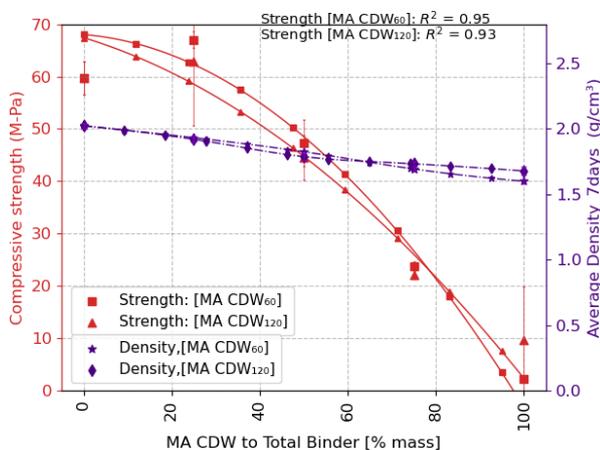


Fig. 6 7-days compressive strengths for varying proportions of MA CDW based binder at 0.3 w/b

$$B = -0.00395X^2 - 0.2565X + 67.44, \quad (5)$$

where:

- units: MPa for coefficients and strength;
- $A, B$ : strengths of 25% MA CDW<sub>60</sub>, MA CDW<sub>120</sub> respectively based binders;
- $X$ : mass % content of CDW in binder.

Beyond 25% MA CDW content, an increase in CDW resulted to decrease in strength, this could be due to significant amount of quartz and crystalline phase for CDW, as illustrated in XRD analysis Table 3, similar to Robayo-Salazar et al. [34] investigated for CDW as precursor in alkaline activated binders. Showed that lower compressive strength for CDW precursor based binder compared with the cement binder at early age (1 and 7 days) was attributed to low CDW reactivity due to high crystalline phase. Also, the trend could be attributed to reduction of cementitious material to react with the pozzolana. The MA CDW<sub>60</sub> had the highest saturated lime pozzolanic reactivity, followed by 120 min ground MA CDW (equated to CDW<sub>120</sub>) [16] while the MA CDW<sub>120</sub> had the highest strengths for MA CDW based samples with 0.5 w/b. Based on the result, the 25% cement replacement was optimum for both particle sizes. The MA CDW<sub>60</sub> based samples at 25% in this case had marginally higher strengths, the result aligning with its pozzolanic reactivity [16]. Partially hydrated cementitious materials enhance the nucleation and renew C-S-H formation process, by diminishing protective layer of C<sub>3</sub>S during pre-induction period [35]. Inconsistency for 25% MA CDW based samples strengths in Fig. 6 compared with corresponding binders in Figs. 4 and 5 could be attributed to variation in of CDW qualities between batches, physical, environmental and experimental factors.

Except for the 25% replacement, all others had reduced strengths as compared with the cement sample, all samples had densities lower than concrete specimen, possibly due to increased pores. The trends could be due to reduced cementitious material and increased pores of MA CDW based materials compared to cement. Harmful pores (larger) for concrete waste based cementitious materials can limit the materials recycling in ordinary Portland cement system, the waste majorly for nucleation sites and filling pores, cannot facilitate substantial strength development [36].

Fig. 7 illustrates the compressive strength test for 25%, MA CDW<sub>60</sub> based binder, with face shearing. Generally, for the varying MA CDW<sub>60</sub> replacements, no shattering occurred but shearing and plastic failures. The MA CDW<sub>120</sub> samples, shear failures at faces were observed.



Fig. 7 Compressive strength test for 25%, MA CDW<sub>60</sub> based binder

### 3.3 Mini-slump cone test and pH

The samples did not flow horizontally even at 0.5 w/b, so the study measured the mini-slump heights, instead of the diameters as stated by Kantro [21]. This phenomenon can be attributed to the fineness of cement (CEM I) material i.e.,  $D_{50}$  of 9.8  $\mu\text{m}$  and specific surface area above 6000  $\text{cm}^2/\text{g}$ , that requires significant water for and CDW characteristics and kinematic reaction, i.e., faster kinetic of mineral hydration with more surface in contact with water that result to faster and more complete hydration, shorting the setting time [37]. The cement and CDW based binders mini-slump cone test results are as illustrated in Fig. 8. No general clear trends occur, with MA or fineness, this could mean that mini-slump is influenced by multiple factors.

Reduced water content from 0.5 w/b (Fig. 4) to 0.3 w/b (Fig. 5) for the CDW based samples reduced the mini-slump heights i.e. reduced workability, Fig. 8, and improved the pozzolanic activity index for MA CDW samples, increasing the compressive strengths and

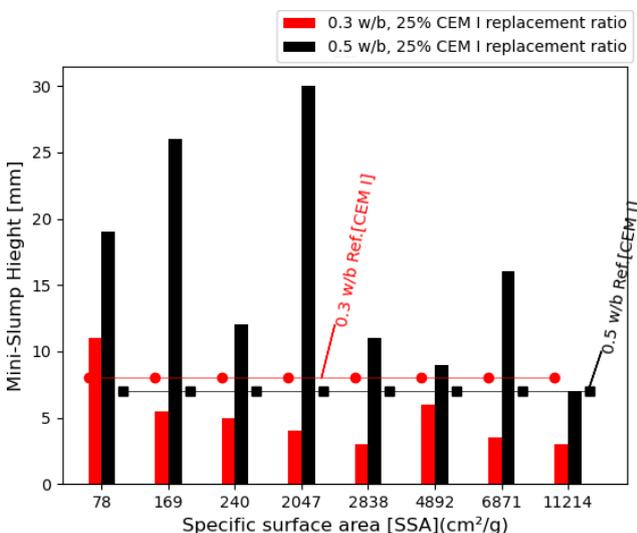


Fig. 8 Mini-slump test for CDW samples NB: incases sample, tampering was conducted to make samples flow out

densities. The 0.5 w/b ratios, the MA CDW<sub>120</sub> and cement mixes had comparatively lower mini-slump heights, this can be attributed to higher water demand by finer material, hence reduced workability. Also the MA CDW<sub>120</sub> based mix at 0.3 w/b was comparatively lower to the majority in that series, which could be attributed to larger SSA hence more kinematic reaction and higher water demand. For 0.3 w/b, with reduced water content, the relatively lower mini-slump heights for MA CDW<sub>15</sub> could possibly due to stiffness of larger and heavier CDW particles (compared with cement and higher grinding time MA CDW), that offered relatively higher resistant to flow. All the mechanically activated based binders had lower slumps at 0.3 water to binder ratios but higher at 0.5 (or almost similar for MA CDW<sub>120</sub> based binder) as compared with cement binder. Lower slump could indicate higher porosity of CDW based samples. Higher slump at 0.5 could indicate increase in fineness after MA of previous cement in CDW. Increase in particle fineness can increase workability, due to increase in mix's flowability [37].

The 0.3 w/b binder, MA CDW<sub>120</sub> and MA CDW<sub>60</sub>, at 25% cement replacement had pH 12.38 and 12.35. The 0.3 w/b for MA CDW<sub>60</sub> at 75, 50, 25 and 0% had pH 12.17, 12.26, 12.43 and 12.40. The 0.3 w/b, MA CDW<sub>120</sub> at 100, 75 and 50% had pH 11.08, 12.53 and 12.40.

Hence, the pH mainly ranged between 12–13. The acidic oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ) for CDW of 60.68%, significantly higher compared to cement's. However, no significant differences in pH compared with cement only based sample. Bagheri et al. [38] showed that at elevated temperatures, in the presence of Al concentration, the Si release rate from amorphous silica reduced with reduced pH, i.e., from 13 to 12.4. Recycled concrete material may adversely affect the environment due to high pH leachate, finer material may result to higher leaching [39]. Compaction may reduce amount of leachate generation due to reduced pores spaces [39].

### 3.4 FTIR analysis

Fig. 9 illustrates the FTIR for selected 25% MA CDW<sub>15,30,60,120</sub> based binders, with  $> 2800 \text{ cm}^2/\text{g}$  MA CDW incorporated samples, for 7-days analysis.

All samples had peaks between 1424 to 1418  $\text{cm}^{-1}$ , exception for CDW<sub>60</sub> wave numbers at those peaks shift towards higher wave numbers, with increasing CDW fineness. Particle size reduction can contribute to the increase in vibrations and bands' intensity, hence frequencies with reduced sizes, also and bands become sharper [5].

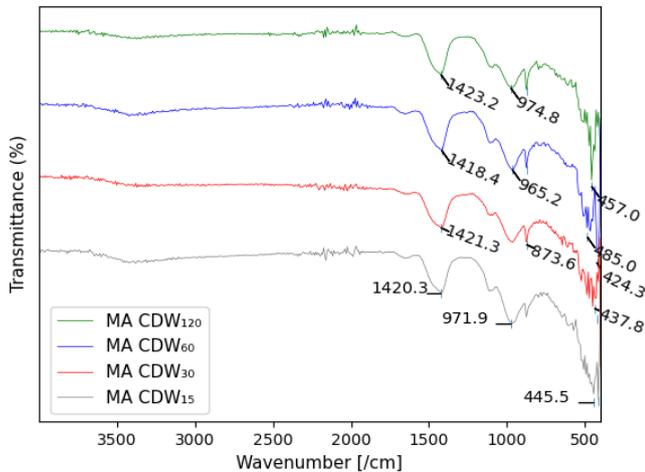


Fig. 9 FTIR for selected MA CDW samples, for cement, MA CDW<sub>15</sub>, MA CDW<sub>30</sub>, MA CDW<sub>60</sub> and MA CDW<sub>120</sub> based binders

Increased bond strength result to a shift towards higher wavenumber, for absorption, the infrared band intensities can be classified as strong, medium or weak [40]. Peaks between 1424 to 1418  $\text{cm}^{-1}$  could be due to  $\text{CO}_3^{2-}$  [5, 41].

Weak peak for all the samples at around 1111  $\text{cm}^{-1}$  could be due to Si-O-Si from quartz [42] of the unreacted CDW. Also, could be due to S-O from ettringite [43, 44]. Hartman and Berliner [45] presented, a detailed crystal structure illustrated for ettringite inclusive of O-H and hydrogen bonds.

Peak occurred in range 975  $\text{cm}^{-1}$ –965  $\text{cm}^{-1}$ , for the MA CDW based samples, with the MA CDW<sub>120</sub> shifting to higher wavenumber (frequency), at this range MA CDW<sub>15</sub> appear more intensified while least for MA CDW<sub>120</sub>. Bernard et al. [46] investigated on with C-S-H samples, the Si-O vibration around 940–970  $\text{cm}^{-1}$  shifted to lower wavelength with increase in Ca/Si, similar to Yu et al. [47] showed similar trend. The shift of MA CDW<sub>120</sub> based sample to higher wavenumber could be attributed to more reactive silica hence reduced Ca/Si ratio compared with coarser based samples. The reduction of particle size contributes to the increase in vibrations and bands' intensity, hence frequencies [5]. The Si-O bond for peaks at around 960  $\text{cm}^{-1}$ , could be due to quartz from the precursor including aggregates ("sand quartz"), that is part of the binder but not eliminated from the sample completely [48], based on the intensities, coarse particles i.e., MA CDW<sub>15</sub> appears to have higher quartz. Peaks in the around 870  $\text{cm}^{-1}$  and 460  $\text{cm}^{-1}$  in the MA CDW based samples, are possibly due to some carbonates [47, 49]. Increase wave number for Si-O possibly indicate increase jennite-like structural environments [47], hence increased intensity of Si-O higher C-S-H [50]. Otherwise, carbonation results in the decomposition of C-S-H to silica and  $\text{CaCO}_3$  [41], hence

the carbonates peaks can be attributed to the the C-S-H decomposition. Also some of peaks around 960  $\text{cm}^{-1}$  may also be due to Al-O [51].

#### 4 Conclusions

Based on the above presented results, towards a carbon neutral concrete production, the following conclusions and recommendations can be drawn:

- The strength vs. SSA series, MA improved the CDW strength, at day 7 compressive strength. Generally increased CDW fineness and SSA resulted in compressive strengths increment. Higher geometric specific surfaces areas averaging  $> 6800 \text{ cm}^2/\text{g}$  had remarkable strengths for 0.3 w/b ratio. Strength increment was possibly due to increased filler effect of the CDW fines in the composite, and more reactive Si for finer mechanically activated materials and greater kinematic reaction with higher SSA, this arguably resulted to the relative reduction of slump of CDW<sub>120</sub> based binder, due to higher water demand. The FTIR shift of MA CDW<sub>120</sub> based sample to higher wave numbers is an indicator of more reactive Si and reduced Ca/Si compared with coarse samples.
- The Strength vs. MA CDW<sub>60,120</sub> content series, the 25% cement replacement resulted to highest strengths. Beyond 25% MA CDW replacement, compressive strengths reduced, this could be due to insufficient cementitious content. Hence MA of CDW at around 25% cement replacement offers possibilities for production of concrete with adequate early age strength development.
- The CDW based series pH was not significantly different compared to cement only sample. However, more future investigation on impact and control for potential leaching on pH is recommended.
- The CDW exhibited higher pozzolanic activity indexes and significantly higher compressive strengths with reduced water content from 0.5 to 0.3 w/b, arguably due to reduced pores after hydration and excess water evaporation. Reduced water content for the CDW based samples reduced the mini-slump heights hence workability, higher strengths ratio for CDW based samples at lower w/b could be due to lower water demand for CDW. At lower water to binder ratios, i.e., 0.3, the study proposes more future investigations with admixtures or superplasticizers.
- Inconsistency in strength and particle sizes could be due to quartz and non-homogeneity between batches

for the CDW. The sizes were determined from > 1 batch aimed at improved particle properties accuracy. Proper quality controls techniques, such as sampling, measuring from multiple batches, should be conducted to ensure that no significant material characteristics deterioration.

- Mechanical activation reduced the loss on ignition, this could reduce negative impact of durability for CDW based binder. Also, with higher Al compared to cement, CDW could offer possibility for chloride binding hence reduced chloride attack, however other effects such as porosity and particle debris should be further studied for durability and long-term mechanical performance up to 25% and > 6800 cm<sup>2</sup>/g MA CDW incorporated concrete. According to Mucsi et al. [5] and Moreno-Juez et al. [8], cited in Section 1, suggest that incorporation of CDW as binder did not have a significant negative impact of > 28 days mechanical performance.
- The shifting of peak frequencies from FTIR is an indication of changes of chemical bonds that can be attributed to MA CDW particle sizes, and also the impact of reacting chemicals.

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