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Effect of Mechanically Activated Recycled Concrete Powder on The Properties of Cement Paste

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ABSTRACT

This study investigates the effect of mechanically activated recycled concrete powder (RCP) on Portland cement mixtures with an RCP content of 20 % is investigated. The setting time tests showed that the inclusion of RCP increased the setting time in almost all cases. However, better results were achieved with the mechanically activated RCP than with the RCP raw material additive. In addition, the final setting time was reduced by almost one hour overall (from 380 min to 325 min) when the 3 minute grind was used, which had a similar setting time to Portland cement. The mixtures showed similar behavior in the rheological tests, with the initial shear stress decreasing slightly after the addition of the RCP. Overall, the compressive strength of the RCP-containing mixtures decreased compared to the cement-containing samples. However, a positive effect of milling was observed, as the lowest compressive strength reduction of 29.34 % was achieved by the RCP ground for 3 minutes.

1. Introduction

In recent years, urbanization has increased extremely worldwide and reached 57 % (World Bank Data, 2018). Such an increase in urbanization and urban transformation is leading to the generation of enormous amounts of construction and demolition waste (CDW) due to construction activities of new buildings and infrastructure, reconstruction or renovation, road construction, expansion of existing structures, maintenance and demolition of dilapidated buildings (Ilcan et al., 2023). Since concrete is one of the most extensively used materials in the world, it is not surprising that concrete waste is one of the largest amounts of CDWs. Worldwide, about 10 billion tons of CDW are generated annually (Ilcan et al., 2023), while in the European Union (EU) in 2022, about 850 million tons (38.4 % of the total waste) were generated in the construction industry (Eurostat, 2022), and this trend shows continuous growth. It is estimated that approximately 35 % of CDW is disposed of in landfills annually without further treatment (Menegaki and Damigos, 2018), despite increasing efforts to recycle and reuse CDW (Luciano et al., 2022). CDW can be recycled in various applications, for example, as aggregates in non-structural concrete (Lotfi et al., 2015; Trivedi et al., 2025), filler material in road bases (Tavira et al., 2020; Khan et al., 2024), subgrades (Zhang et al., 2020), an adsorbent material (dos Reis et al., 2020; Pallewatta et al., 2023), and soil conditioner (Santos and Tubino, 2021; Greinert et al., 2024). Recently, extensive research has also been conducted on the utilization of CDW in

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geopolymer/geopolymer concrete applications (Tan et al., 2020).

Concrete waste is mainly used as a coarse aggregate to produce new concrete. The use of recycled concrete aggregate (RCA) in concrete production is limited to low-strength concrete due to difficulties in quality control and poor strength. On the other hand, during the preparation of waste concrete, concrete powder (CP) as a fine (dust) size fraction (< 75 μm) is generated in appr.10 wt. % (Figueiredo et al., 2018). The CP, which is mainly derived from the cement stone part of concrete, can be used as a replacement material for cement (Cantero et al., 2020; Dacić et al., 2023; Deng et al., 2023). However, the reactivity of recycled concrete powder (RCP) in its current form is low and should be improved so it can be used as a pozzolanic material. Mechanical activation (MA) is one of the effective ways to improve the reactivity of solid materials, as a result of which, in addition to the decrease in particle size and increase in specific surface area, the structure of the material may usually become disordered and defects or other metastable forms may be formed (Juhász and Opoczky, 1990). For MA, different mills can be used like planetary mills (Chen et al., 2021; Wu et al., 2022; Gao et al., 2025), ball mills (Cantero et al., 2020; Kong et al., 2025), and stirred media mills (Mucsi et al., 2021; Szabó et al., 2023). At the same time, the optimal fineness is very important, as the fineness of the RCP has a strong influence not only on the hydration process (Chen et al., 2021; Li et al., 2022; Deng et al., 2023; Xue et al., 2025) and, thus, the strength (Cantero et al., 2020; Chen et al., 2021; Mucsi et al., 2021; Du et al., 2023), but also on the workability (Cantero et al., 2020; Deng et al., 2023) and setting time (Wu et al., 2022; Li et al., 2023). From the literature, it can be concluded that the ball mill is most commonly used to produce RCP, but only a few studies (Mucsi et al., 2021; Szabó et al., 2023) deal with the properties of products made using RCP produced in a high-energy density mill (e.g. stirred media mill).

The research aims to investigate the effect of mechanical activation of RCP in a high-energy density mill on the setting time and rheology of the cement paste and to study the relationships between the mechanically activated RCP and the properties of the new product.

2. Material and methods

2.1. Material characterization

The RCP from waste concrete and Portland cement were used for the experiments. The initial particle size of the waste concrete was <20 mm (median particle size, x_{50}=6.0 mm) and it came from Mento Ltd. (Bodrogkeresztúr, Hungary), while the cement was slag Portland cement with a high initial strength of 42.5 MPa standard strength according to MSZ EN 197-1 (CEM II/A-S 42.5 R), from LAFARGE-Cement Hungary Ltd, Hungary. The main characteristic particle sizes of the cement were as follows: x_{10}=5.57 μm, x_{50}=12.74, and x_{90}=24.69 μm.

Several studies have found that impact, rubbing, and abrasion can be effective solutions for removing mortar adhering to the surface of aggregates (Nagataki et al., 2004; Quan, 2011; Tam et al., 2021). However, during mechanical grinding, the RCA can be more easily damaged and broken into finer fractions, increasing its proportion in the cement stone powder and thereby degrading the properties of the RCP (Tam et al., 2021).

Considering all this, to recover the RCP, as a first step, the fine fraction (<200 microns) was removed with sieving, and then the coarse fraction was subjected to low-energy selective milling (SM) in a laboratory-scale drum mill at low speed (50 rpm) for 60 min, as a result of which the kinetics of fragmentation occur by autogenous abrasion.

Due to the abrasion of the concrete, a higher amount of RCP could be obtained, which was sieved below 200 μm.

The particle size distribution (PSD) of the RCP was measured with a HORIBA LA-950V2 laser diffraction particle size analyzer in wet mode using alcohol as dispersing media.

The geometric specific surface area (SSA) was calculated using PSD data by the laser sizer software. The median particle size and SSA of the RCP were found to be 20 μm and 2715 cm^2/g, respectively. The particle density was determined using the pycnometer method, with isopropyl alcohol as the medium. The bulk density and particle density of the RCP were 0.88 and 2.47 g/cm^3, respectively.

The mineralogical composition of the RCP, which was determined with a Bruker D8 Advance X-ray powder diffractometer (XRD) (Cu-Kα radiation, 40 kV, 40 mA) in parallel beam geometry (Göbel-mirror), is presented in Table 1.

The amorphous content was determined using the amorphous hump method, which has been successfully applied in several research involving silicate rocks (Németh et al., 2023) and alkali activation products (Kumar et al., 2017), where the XRD data was correlated with chemical composition or by direct comparison of the internal standard and the hump method (Ahmad et al., 2018).

Based on Table 1, it can be concluded that a significant proportion of the RCP is quartz and carbonates derived from the fine aggregate (sand) of the waste concrete and hydrated cement.

Table 1
Mineralogical composition of RCP (Szabó et al., 2023)

Phase name	**RCP (wt. %)**
Quartz	54.4
Muscovite 2M1	4.0
Calcite	9.7
Vaterite	6.3
Albite	6.1
Orthoclase	3.0
Chlorite IIb	0.6
Ettringite	0.3
Portlandite	0.2
Actinolite	0.4
Amorphous	15.0

2.2. Mechanical activation

The disc-stirred media mill used for MA is equipped with a ceramic liner and a built-in cooling system, and the effective volume of the mill is 530 cm^3. The filling ratio of both the material and the milling beads (zirconium silicate "ZS type", Ø 1-1.2 mm ceramic beads) was 70 %. The mill was operated at a rotor speed of 5 m/s. The applied milling times were 1, 3, and 5 min.

The 0 min milling refers to the pre-processed raw RCP sample (RCP0) that was not mechanically activated in the stirred media mill. The mechanically activated RCP samples obtained as a result of milling were labeled MARCP1, MARCP3, and MARCP5, where the numbers indicate the milling time.

2.3. Setting time

The initial and final setting times of all pastes were tested according to the Hungarian standard (MSZ EN 196-3, 2017) using a standard Vicat apparatus. The water/binder (w/b) ratio was 0.33 in all cases. The RCP replacement rate was determined based on previous research (Szabó et al., 2023). Based on this, 20 % of the solid material (cement) of the paste was replaced by RCP of different fineness obtained during MA. The consistency and flowability of all samples were appropriate for the Vicat setting time tests. The paste was placed into the Vicat mold, and the Vicat needle was lowered into the paste at regular intervals. The initial setting time was recorded when the penetration was no longer possible at a specified depth (distance between the needle and the glass plate 4±1 mm), while the final setting time was recorded when the needle did not sink more than 0.5 mm into the hardened cement paste. As a reference, the setting time of the cement paste (CP) without RCP was also investigated.

2.4. Rheology

The flowability of the pastes was determined by measuring the change in shear stress as a function of the change in shear rate (s^{-1}) at a given RCP content (20 % w/w) but at different RCP finenesses using an Anton Paar Physica MCR 51 type rotational rheometer with cylinder-cylinder measuring head. The shear rate was 1000…100 s^{-1}, starting at the highest shear rate value to avoid the sedimentation of small particles during the test. The rheometer is equipped with the Rheoplus data collector software to record the shear stress values. For reference, the rheology of the CP without RCP was also studied. The w/b ratio was 0.38 in all series. Furthermore, two measurements were taken for each series, and the values obtained were averaged.

2.5. Mechanical strength

The specimens used for strength tests were obtained by mixing cement, RCP, and water. The w/b ratio was kept at 0.33. The pastes were cast in cubic molds and compacted for 1 minute on a vibrating table. After 24 hours, the specimens were de-molded and stored under water until the compressive strength test. The uniaxial compressive strength of 20 mm cube specimens was tested at the age of 7 days using an SZF-1 type hydraulic compression testing machine with a maximum load of 25 kN. Five specimens were tested in each series and the strength values were averaged.

2.6. Structure

Structural analyses of the mechanically activated RCP and hardened pastes were performed by Fourier Transform Infrared (FTIR) spectroscopy, by which bending and stretching vibrations of chemical bonds in the samples were detected by a JASCO FT-IR 4200 type Fourier Transform Infrared Spectrometer in reflection mode and a diamond ATR.

After the mechanical strength tests, the powdered samples and pieces of the broken specimens were crushed in a mortar to a suitable particle size (~15-50 µm) for effective FTIR testing. The spectra were recorded in the absorption range from 4000 to 400 cm^{-1}. The spectra were baseline corrected, and each spectrum was an average of the results of 3 runs.

3. Results and Discussion

3.1. Mechanical activation

The effect of MA on the particle size distribution of RCPs can be seen in Figure 1, while the characteristic particle sizes (x_{10}, x_{50}, and x_{90}) and the "outer" geometric SSA of RCPs are shown in Table 2. Based on the results, it can be stated that milling resulted in a decrease in the particle size of MARCPs, while the SSA increased.

However, after 1 minute of milling, there was no significant reduction in the particle size of the MARCP, which can be attributed to the phenomenon of aggregation and agglomeration. A significant amount of the small particles (a few hundred nanometers) produced during milling adhered to each other and to larger particles (about 100 microns), increasing in particle size, and therefore no significant change in SSA. Similar statements were made by Zhang et al. (2022), who found that mechanical activation (in a planetary ball mill) helped to modify the particle size and distribution of RCP. At the same time, it was observed that beyond a certain grinding time (60 min), the reduction in particle size was not significant, which did not result in an increase in strength.

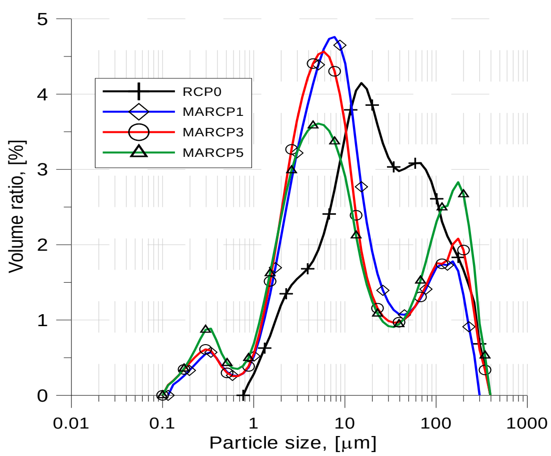

Figure 1. Particle size distribution by volume of the RCPs

Table 2
The characteristic particle size and SSA values of the raw and mechanically activated RCPs

Milling time (min)	x_{10} (μm)	x_{50} (μm)	x_{90} (μm)	SSA (cm^2/g)
0	3.28	20.22	126.67	2,715
1	1.64	8.42	98.80	8,614
3	1.51	6.67	129.20	10,070
5	1.22	7.65	159.40	10,832

3.2. Setting time

The incorporation of RCP has a two-sided effect on the setting time of the paste. On the one hand, the incorporation of RCP reduces the amount of hydrated products in the paste, thereby increasing the setting time (Wu et al., 2022; Zhang et al., 2023). On the other hand, RCP particles function as crystallization nuclei, promoting the formation of hydration products and reducing the setting time (Tang et al., 2020; Wu et al., 2022; Kaptan et al., 2024). Figure 2 shows the initial and final setting times of the paste containing RCP with different fineness. The setting time results showed that the inclusion of the RCP increased the setting time in all cases. In particular, when using low fineness RCP0, the increase in setting time is more noticeable due to the reduction of hydration products in the paste. However, when MARCPs were used, both the initial and final setting times of the paste were shorter compared to the RCP0-containing paste. Compared to CP, the initial and final setting times of RCP0-CP increased by 23.3 % and 18.8 %, respectively, while the initial and final setting times of MARCP3-CP only increased by 7.0 % and 1.5 %, respectively. A similar finding was made by Zhao et al. (2020) and Wu et al. (2022), according to whom high-fineness recycled brick powder and RCP helped to reduce the initial and final setting time of the paste, as the high reactivity of the brick powder and RCP accelerated the formation of hydration products. It can also be seen that the initial setting time of MARCP5-CP was the same as that of MARCP3-CP, but the final setting time was significantly longer than that of MARCP3-CP. This can be explained by the fact that the more reactive fine particles of MARCP5 accelerated the initial setting time as a result of more intense hydrated product formation, while the presence of agglomerated coarse particles resulted in the formation of less hydrated product in the later setting phase, thereby increasing the final setting time.

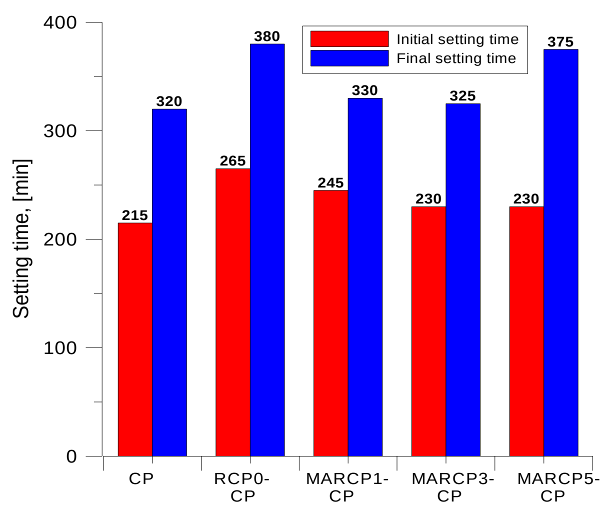

Figure 2. Setting time of the paste with different rcp fineness

3.3. Rheology

Figure 3 shows the flow curves of the plain CP and CP with a different fineness of RCP. From Figure 3, it can be concluded that the blends showed similar behavior during the rheological tests according to the Herschel-Bulkley model, with a slight decrease in initial shear stress after the addition of RCP. No clear trend can be observed in the flow behavior of the pastes when using RCPs of different fineness, but it can be related to the particle size and SSA of MARCPs. MARCP1-CP showed similar flow behavior to CP, while RCP0-CP had the lowest flow resistance. According to Deng et al. (2023), the fluctuation of the rheological parameters of cement pastes is closely related to the dosage and fineness of the RCP. They found that the yield stress and plastic viscosity of cement paste significantly increased with the increase of recycled fine powder (RFP) content.

This can be explained on the one hand by the fact that the RFP particles resulted in higher water absorption and less free water in the slurry, on the other hand, due to the wider particle size distribution and more regular surface morphology of the RCP particles, there is less possibility of friction and adhesion between the particles during the shear test.

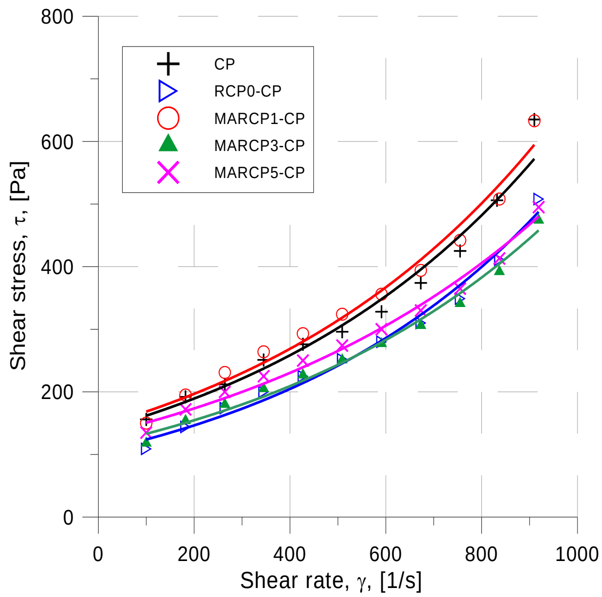

Figure 3. Flow curves of the pastes with different RCP fineness

3.4. Mechanical strength

Figure 4 presents the compressive strength of paste including RCP at different fineness. From this Figure, it can be concluded that the addition of RCP at different fineness resulted in lower strength in all cases compared to the CP sample. However, the positive effect of MA was observed, as the lowest compressive strength decrease of 29 % was achieved by MARCP3-CP when the strength value decreased from 68.8 MPa to only 48.6 MPa. The sample with the non-activated RCP content (RCP0-CP) had the lowest strength (39.4 MPa). This is also supported by the findings of Wu et al. (2022) that the negative effect of coarse RCP on mechanical strength is greater than the negative effect of fine RCP on mechanical strength. This is because the use of coarse RCP can reduce the filler effect and pozzolanic activity of RCP. The positive effect on mechanical strength can be explained by the fact that the more reactive, finer RCP improved the dissolution and precipitation process of cement hydration, thereby creating a denser (less porous) structure (Deng et al., 2023). At the same time, it can also be stated that with the extension of grinding time, the agglomeration effect between RCP particles was enhanced, which weakened the filling effect of RCP and adversely affected the strength of MARCP5-CP (Shen et al., 2023). Xue et al. (2025) found that as the RCP particle size decreased, the RCP activity index first increased and then decreased, indicating that the fineness of RCP is not better, the finer, and there is an optimal fineness. They also stated that RCP mainly exerts a physical filling and nucleation effect and some puccolan effect on the cement-RCP system. The smaller RCP particle size provides more nucleation sites for cement and hydration products.

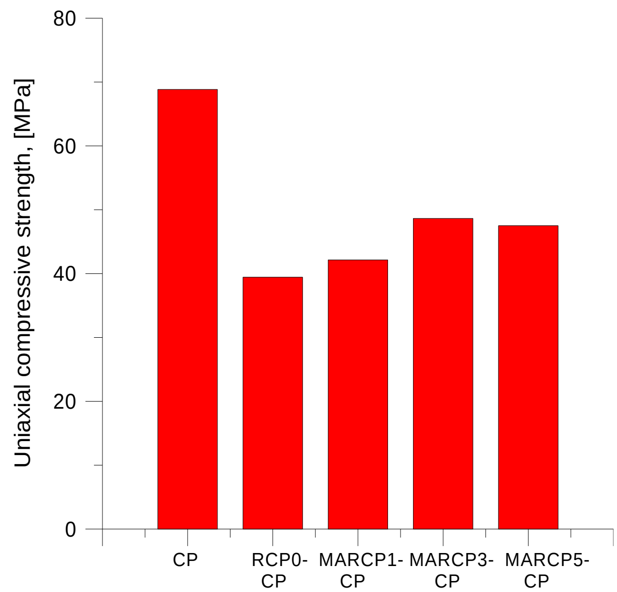

Figure 4. Compressive strength of the samples

3.5. Structure

The FTIR spectra of the cement and RCPs with different fineness can be seen in Figure 5. In the case of the cement spectrum, the bands at 1428 and 873 cm^{-1} can be assigned to CO_3^{2-} stretching vibrations. The weak band at 1,113 cm^{-1} is the indication of Si–O–Si stretching vibrations, and the band at 521 cm^{-1} corresponds to the Si–O deformation vibrations of the siliceous phases

(Amor et al., 2018; Cho et al., 2018; Szabó et al., 2023). The spectra of the RCP0 and MARCPs show prominent vibrations at 1,428, 1,010, and 874 cm^{-1}, respectively, which can be attributed to $\nu3$-CO_3^{2-} stretching, Si-O-Si stretching, and $\nu2$-CO_3^{2-} stretching vibrations; these arise from the $CaCO_3$ and calcium silicate (C_3S and C_2S) phases, which are the main constituents of cement (Cho et al., 2018; Li et al., 2025). The broad band at ~3416 cm^{-1} in the spectrum of RCPs corresponds to the O–H stretching, and the weak band at 1614 cm^{-1} corresponds to the O-H bending vibration, indicating the presence of small amounts of structural and weakly bound water in the samples. The bands at 796, 779, and 694 cm^{-1} show the presence of quartz (Mucsi et al., 2021). Compared to the RCP0 sample, the FTIR spectra of MARCPs show a difference in the intensity of some bands. As a result of milling, the intensity of bands (796, 779, and 694 cm^{-1}) referring to quartz decreased.

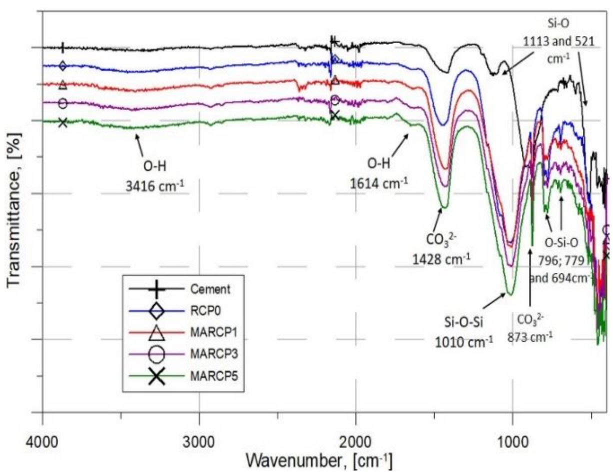

Figure 5. FTIR spectra of the cement and RCPs with different fineness

Figure 6 shows the FTIR spectra of the cement pastes. The bands referring to hydrated phases are discernible in the spectra of all samples. The wide band at around 3,375 cm^{-1} is attributed to the symmetric stretching vibration of the H_2O molecule, while the narrow, unique band at 3,640 cm^{-1} can be assigned to the presence of portlandite ($Ca(OH)_2$) (Horgnies et al., 2013; Lu et al., 2018). It can also be seen that in each paste there are two strong bands between 1,430 cm^{-1} and 873 cm^{-1}, which can be attributed to the in-plane and out-of-plane bending vibrations of CO_3^{2-}, respectively. Additionally, the bands at 1,416 and 873 cm^{-1} were wide, which was clear evidence of the presence of amorphous $CaCO_3$ (Lu et al., 2018; Li et al., 2025). The intensity of these bands is greater in the case of finer MARCP-containing pastes. The band at around 960 cm^{-1} refers to Si–O stretching vibrations, indicating a wide range of C–S–H with Ca/Si ≈ 2 (Pan et al., 2017). The intensity of this band can be related to the fineness of the RCP. The MARCP1-CP sample had the highest band intensity.

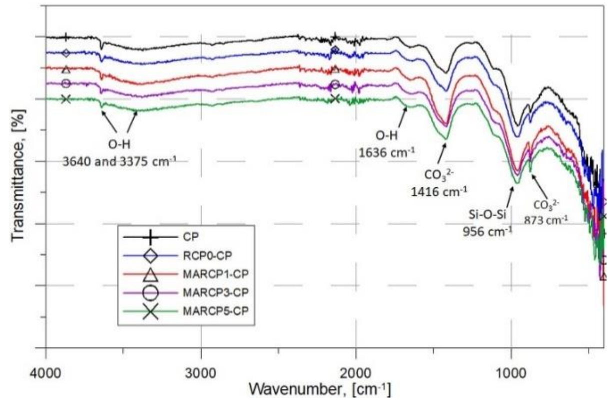

Figure 6. FTIR spectra of the specimens

6. Conclusions

This paper investigates the influence of RCP of different fineness on the early cementing behavior and performance of hardened cement paste. Based on the experimental results, the following conclusions can be drawn:

1. Compared to cement, RCP has a wider particle size distribution and a significant SiO_2 content (mainly quartz). The inert components in RCP resulted in low activity.
2. When MARCP was used, both the initial and final setting times of the cement paste were shorter than for the paste with RCP0, as MARCP with higher reactivity accelerates the formation of hydration products.
3. The finer particles of MARCP improved the rheological properties of the paste due to their higher water absorption capacity, which reduced the free water in the slurry.
4. The use of RCP resulted in a lower performing CP. However, the MARCP-CPs showed better strength compared to the RCP0-CP. At the same time, the optimization of the mechanical activation process is very important as there was significant aggregation and agglomeration of the particles after 1 minute of milling, resulting in a lower strength of the sample due to the reduced dissolution and precipitation process of cement hydration.

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Uticaj mehanički aktiviranog praha recikliranog betona na svojstva cementne paste

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I Z V O D

Ova studija istražuje uticaj mehanički aktiviranog praha recikliranog betona (PRB) na mešavine portland cementa sa udelom PRB-a od 20 %. Testovi vremena vezivanja pokazali su da dodatak PRB-a produžava vreme vezivanja u gotovo svim slučajevima. Ipak, bolji rezultati su postignuti upotrebom mehanički aktiviranog PRB-a u poređenju sa dodatkom sirovog PRB-a. Pored toga, konačno vreme vezivanja je ukupno smanjeno za skoro jedan sat (sa 380 minuta na 325 minuta) kada je korišćeno mlevenje u trajanju od 3 minuta, pri čemu je postignuto vreme vezivanja slično onom kod portland cementa. Mešavine su pokazale slična ponašanja u reološkim testovima, pri čemu je početni napon smicanja blago opao nakon dodavanja PRB-a. Ukupno posmatrano, pritisna čvrstoća mešavina koje sadrže PRB bila je smanjena u odnosu na uzorke koji sadrže samo cement. Međutim, zabeležen je pozitivan efekat mlevenja, jer je najmanje smanjenje pritisne čvrstoće, od 29,34 %, postignuto PRB-om mlevenim u trajanju od 3 minuta.