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Investigation of Waste Perlite and Recycled Concrete Powders as Supplementary Cementitious Materials

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Abstract

One of the sustainable solutions for cementitious materials could be the inclusion of locally available raw materials with possible lower environmental and/or economic impacts that meet technical requirements. This study focuses on waste perlite and recycled concrete powders, which are wastes from natural or artificial rock. Their effects on hardened and fresh properties were investigated by cement replacement of 15, 30 and 45 m%. The waste perlite powders demonstrated higher reactivity, while the recycled concrete powder would act mainly as a filler material. When using recycled concrete and waste perlite powders, an adverse effect was identified on the examined fresh properties.

Keywords

supplementary cementitious material, waste perlite powder, recycled concrete powder

1 Introduction

The extensive utilization of cement results in about 12–15% of the overall industrial energy consumption and reaches up to 8% of global anthropogenic CO_2 emissions [1]. Additionally, as a part of concrete, cement can correspond to about 45% of concrete's cost [2]. Although supplementary cementitious materials (SCMs) as partial clinker replacement are getting widespread, the traditional ones (e.g., blast furnace slag and fly ash) are getting scarce, leading to the investigation of alternative sources [3]. In general, aluminosilicate and silica SCMs can be divided into three main groups, namely pozzolanic, hydraulic and inactive/hardly reactive materials. This classification is mainly based on their chemical and phase composition, resulting in the reactivity in hydrating cement systems [4]. In facing the challenge of urban development and reducing cement's environmental burden, a regionalized approach could be a solution by employing locally available resources to generate more sustainable practices. Globally, quarry practices have substantially affected ecological equilibrium [5]. Hence, this study focuses on investigating locally available waste products that could be used as cement replacements. While perlite is a naturally occurring rock, concrete is an artificial stone abundant as construction and demolition waste worldwide.

Perlite is commonly referred to as a naturally occurring siliceous volcanic rock usually mined by opencast methods. It has a characteristic feature of expanding approximately 5–20 times its original volume when heated at around 900–1200 °C. The expanded perlite was first produced in the USA in 1953. Ever since, it has been used as an aggregate in mortars, plasters, lightweight concrete, thermal insulation, etc. [6]. The expanded perlite is utilized as a construction product, agricultural aggregate, filter aid and filler [7]. In 2020 the total amount of perlite produced worldwide was 4.22 million tons. Solely in Hungary, production in 2020 was estimated to be about 80 thousand tons. Worldwide the five largest producers corresponding to about 94% of total production, aside from the USA and Hungary, are China, Greece and Turkey [8]. Two types of waste powder used in this study were obtained from the perlite production milling and grading system. WPP-C designates the dust collected from the cyclone while WPP-SZ from the baghouse [9].

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On the other hand, investigations and applications of recycled concrete aggregate have been extensive for decades. Although the usage of recycled concrete aggregate has been introduced as one of the sustainable solutions in the concrete industry, further research is needed to make the product more appealing from an economic, environmental and technical perspective. When the construction and demolition concrete waste is crushed to produce aggregate, there is also waste produced as a powder. It is estimated that the amount of paste/mortar in waste concrete is approximately 20–50% [10]. In this study, the powder was generated during the crushing process of recycled concrete aggregate by jaw crusher and sieving. During the sieving procedure, the particles passing 63 μm sieve size were collected for investigation as cement replacement. It would be highly beneficial if all recycling components could be used in cementitious products.

2 Background

When evaluating the effect of SCMs, it is essential to define the adequate replacement levels for which they would not have an adverse effect on both the fresh and hardened properties of the cementitious materials. Despite the fresh state of cementitious materials being only temporary, the strength and other durability properties are significantly affected by the degree of the compaction. Hence, the consistency of a mix must be such that it can be transported, placed, compacted and finished easily and excluding segregation [11]. Yu et al. [12] investigated perlite powder utilization in concrete and concluded that based on the compressive strength, its pozzolanic effect is significant and can be considered an active mineral admixture. The usage of perlite as a pozzolanic additive in blended cements was the focus of the study by Erdem et al. [13]. They produced 16 types of blended cements using 20% or 30% replacement ratios for perlite. The results showed that it has a sufficient pozzolanic activity to be used as an addition to blended cements. On the other hand, for the blended cements a higher water dosage was required compared to Portland cement to have standard consistency [13].

Moreover, calcinated perlite powder was investigated as SCM by Ramezanianpour et al. [14], where partial replacement of cement was utilized in concrete samples. Compressive strength and chloride ingress results were presented, showing that a decrease in compressive strength with calcinated perlite powder inclusion was insignificant, while permeability was improved [14]. El Mir and Nehme [15] examined the usage of waste perlite powder (WPP) as filler material in self-compacting concrete. They showed that its incorporation positively impacts concrete's microstructure, compressive strength and durability. Hence, its pozzolanic activity could be recognized. They also demonstrated that the high range water reducing admixture demand of a mixture containing WPP was 2.5–4 times more than that of incorporating limestone powder [15]. Furthermore, the incorporation of WPP as cement replacement in the production of recycled aggregate self-compacting high strength concrete showed beneficial results in mechanical properties with up to 15% substitution. Additionally, it was demonstrated that fresh properties were negatively affected when WPP was used. The required amount of high range water reducing admixture substantially increased. This phenomenon was attributed to the high surface area and absorption capacity of the WPP material [16]. However, the studies did not consider separately different types of the WPP and the possible effect on pozzolanic activity. Hence, this study investigates two different WPPs trying to characterize their effect on cementitious materials' hardened and fresh properties.

Ma and Wang [10] investigated the effect of the ground waste concrete powder obtained by crushing and grinding the concrete specimens on cement properties. They concluded that the reduction in strength is insignificant for a replacement ratio of ground waste concrete powder lower than 20%. However, for higher replacement ratios, the decrease was evident. An increase in ground waste concrete powder's amount led to lower water demand for normal consistency. This was attributed to the low presence of unhydrated C2S, which slowly reacts and other minerals that do not react with water. Also, for the same water/binder ratio, the fluidity of the cement mortar is raised with the inclusion of ground waste concrete powder [10]. On the contrary, Xiao et al. [17] utilized recycled powder (RP) generated from construction and demolition waste, which also contained fired brick. Incorporation of the RP in concrete had a positive or minimal negative influence on the mechanical properties when the replacement rate of cement was up to 30%. However, for the substitution higher than 45% detrimental effect was substantial. On the other hand, the amount of water-reducing agent increased almost linearly with the increase in RP replacement ratio. The high-water absorption and irregular microstructure were identified as influential for such behavior [17].

Moreover, Li et al. [18] conducted an experimental study regarding the preparation of recycled admixtures by using construction and demolition waste. The study covered three types of RPs: RP generated from reshaping of recycled concrete aggregate (RCP), RP prepared with waste clay brick and mortar blocks (RBP) and recycled mortar powder (RMP). It was concluded that the presence of RBP in hybrid RP is the most influential. When its content is above 50%, the requirements of fly ash could be met. The results showed that the water requirement ratio of the fluidity of the mortar mixed with RP and the reference mortar (ordinary Portland cement) was minimum in the case of RBP (105%). While for RMP and RCP, the values were 107% and 111%, respectively. On the other hand, mortars containing RBP had the highest fluidity, followed by RMP and RCP [18]. Additionally, a study on RCP and RBP as SCMs by their incorporation in mortar showed that the activity index representing the pozzolanic activity of the SCMs for RBP ranged between 82% and 87% at 90 days and for RCP, it was between 72% and 78%. They concluded that the incorporation of RCP led to a significant decrease in the initial fluidity. In general, a decrease in initial fluidity with the rise in fineness was observed. On the contrary, the decrease was minor for mortars containing the RBP. The fluidity increased slowly as the RBP's fineness raised. This was attributed to the possible interaction effect between the minor increase in the specific surface area (SSA) and improved particle morphology and gradation. However, the inclusion of RCP showed a significant decrease in the workability of the mortar. This could be due to the high external surface area and porosity [1]. In the current study, RCP was solely originating from the production process of recycled concrete aggregate. Although some impurities were recognized, it can be considered that the source was mostly concrete. Hence, it is expected that this study would give more insight into the possibility of the entire utilization of this recycling process' products. This would be beneficial for the next stages of the study, where recycled aggregate concrete will be produced with the goal to use as much as possible green raw materials.

3 Materials and methods

3.1 Materials

The cement used was CEM I 42.5 N with the specific gravity (SG) of 3.17 and an SSA of 396 m^2/kg (Table 1). As stated above, two types of WPP were used for the investigation, which differed in the SSA. In order to evaluate the effect of RCP and WPP on the properties of the cementitious material, mortar specimens were also prepared, which are more representative of concrete than cement paste. For this purpose, CEN standard sand confirming to MSZ EN 196-1 and tap water were used [19]. The test performed for the determination of SSA of the powders was based on the Blaine method (for CEM I 42.5 N, WPP-C and RCP - MSZ EN 196-6; for WPP-SZ - ASTM C 204) [20, 21]. Additionally, results considering laser scattering analyzer (LSA) are presented in Table 1. Out of WPPs, one with the larger SSA is denoted as WPP-SZ and one with lower as WPP-C. RCP had higher SG than WPPs, while its SSA was lower than WPP-SZ's and higher than WPP-C's. Consequently, the powders differed in the particle size distribution (Fig. 1). In Fig. 2(a)–(c), scanning electron microscope (SEM) images of the powders are presented, where the size differentiation is visible (the same magnification was used). Moreover, as expected, the shape of the used powders is angular, which is typical for products of the crushing process. The angular shape of particles is characteristic of ordinary Portland cement, too. The median diameters (D_{50}) for all the samples are also presented in Table 1.

The values regarding the loss on ignition (LOI) also differed greatly for different types of powders (Table 1). The procedure for the test followed MSZ EN 196-2, where the used temperature was 975 °C. To avoid discrepancies, the powders were oven-dried to a constant temperature before the test [22]. In MSZ EN 197-1 upper limit for LOI in the case of cement is 5%, silica fume 4%, and fly ash 5%, 7% and 9% [23]. While in ASTM C 618 requirement for

Table 1 Characterization of used cement, recycled concrete (RCP) and waste perlite powders (WPPs)

	SG [-]	SSA (Blaine) [m^2/kg]	SSA (LSA) [cm^2/cm^3]	D_{50} [μm]	LOI [%]
CEM	3.17	396	7340	12.31	2.38
RCP	2.50	351	4328	25.29	17.13
WPP-C	2.43	176	1972	43.14	4.25
WPP-SZ	2.43	1132	6761	10.19	5.12

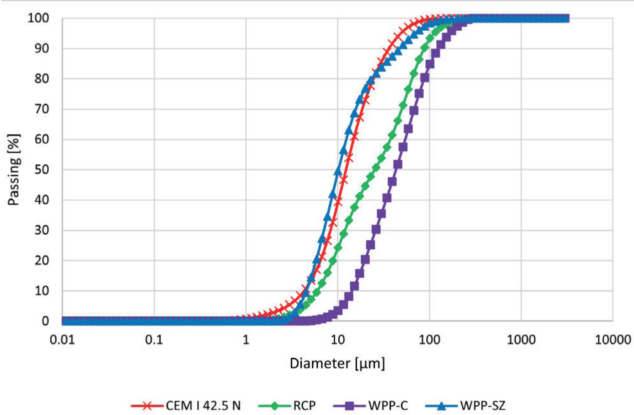
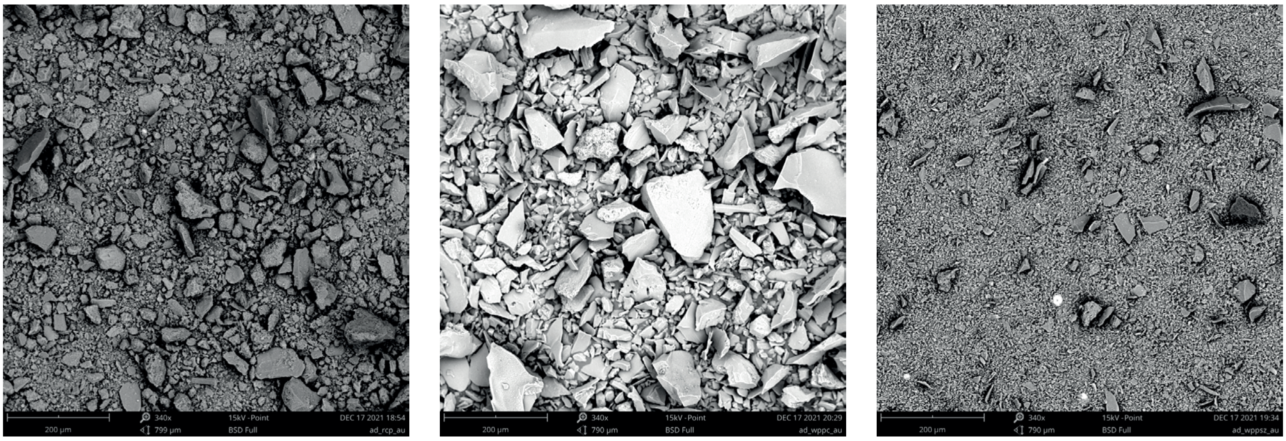


Fig. 1 Grading curve for the cement, RCP and WPPs



(a) (b) (c)

Fig. 2 SEM images of (a) RCP, (b) WPP-C and (c) WPP-SZ

maximum LOI for natural pozzolans is 10% [24]. However, in the case of ASTM C 311, the test is performed at a lower temperature of 750 ± 50 °C [25]. The WPPs can be considered as conforming to the requirements. The increase in the value was most profound in the case of RCP, which was probably mainly due to the carbonation of concrete during the service life, storage and grinding and sieving procedure on atmospheric conditions. The presence of carbonate can also be confirmed by thermogravimetry (TG). The derivative thermogravimetry (DTG) peak of RCP at about 800 °C indicates the presence of $CaCO_3$, which is the product of the $Ca(OH)_2$ and airborne CO_2. The low thermogravimetric mass change in case of WPPs is mainly due to the loss of colloidal water (Fig. 3). In order to conform to ASTM C 618, the chemical composition of the SCM should consist of at least 70% by the sum of SiO_2, Al_2O_3 and Fe_2O_3 [24]. The main constituents of perlite ore are SiO_2 and Al_2O_3, with lower amounts of other oxides such as Fe_2O_3, Na_2O, K_2O, CaO and MgO [26]. The chemical composition of the SCM was obtained using SEM-EDS (scanning electron microscopy with energy dispersive spectroscopy). In the case of WPP-C sum of SiO_2, Al_2O_3 and Fe_2O_3 is equal to 90.49%, while for WPP-SZ 90.75%. On the other hand, for RCP this value is equal to 62.04%. Solely SiO_2 amount is 74.47% and 73.09% for WPP-C and WPP-SZ, respectively (Table 2). Overall, RCP seems to have a more heterogeneous chemical composition than WPPs. This can be explained by the fact that it is mainly a combination of aggregate and hardened cement paste.

Table 2 Chemical composition of RCP, WPP-C and WPP-SZ

	RCP	WPP-C	WPP-SZ
SiO_2	48.69	74.47	73.09
Al_2O_3	9.00	13.80	14.71
Fe_2O_3	4.35	2.22	2.95
CaO	30.94	1.45	1.47
K_2O	1.81	5.21	4.97
Na_2O	0.94	2.43	2.21
MgO	2.73	0.21	0.39
SO_3	1.04	0.00	0.00
Others	0.50	0.21	0.21

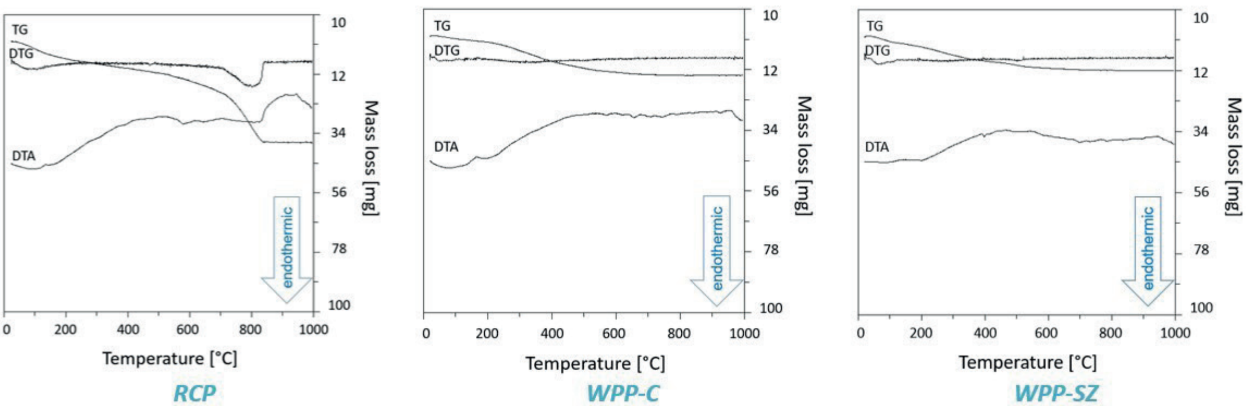


Fig. 3 TG/DTG/DTA curves of RCP, WPP-C and WPP-SZ

Moreover, the amorphous character of WPPs was observed through X-ray diffraction patterns (Fig. 4) [13]. In the case of RCP, we can differentiate between minerals with Ca and Si. The Ca containing crystal diffraction peaks mainly correspond to the cement paste while Si is originated mainly from the quartz type aggregate.

However, TG method is widely used for the characterization of SCMs and can be considered as an incremental LOI test, whereupon the fixed heating rate, the mass of the specimen is recorded (Fig. 3) [27]. While DTG represents the first derivative of the TG curve, differential thermal analysis (DTA) is a technique where the difference in temperature between a sample and reference materials is measured while both are subjected to the same controlled temperature program [28]. The DTA curve provides information on whether the thermal reaction is endothermic or exothermic.

In the case of hydrated cement (cement paste), there are few characteristic temperature ranges regarding weight loss due to heating. In the first range between 25–320 °C, dehydration of ettringite or other calcium aluminum hydrates (C-A-H) and calcium silicate hydrate (C-S-H) gel are present. In the phases between 450–550 °C, the dehydration of portlandite, while from 650 to 900 °C calcite decarbonation occurs [28, 29]. If we consider the presence of silica aggregate (quartz), its structure might alter to various SiO_2 polymorphs when heated [30]. Its crystal transition temperature is between 573 and 575 °C, corresponding to the transformation of α- to β-quartz as an endothermic reaction during heating with an increase in volume by 0.4% [30, 31]. Hence, even the deterioration of the concrete exposed to high temperatures is attributed to the thermal mismatch between the expansion of silica aggregates and the shrinkage of the cement paste matrix [29]. As shown in Fig. 3, mass loss during the decarbonation of the calcite phase (650–900 °C) was the most significant, emphasizing the carbonation property of concrete. Additionally, at around 450 °C, a small peak in the DTG curve is visible, referring to dehydration of portlandite. Moreover, calcite decomposition can also come from the usage of limestone either as a filler or aggregate.

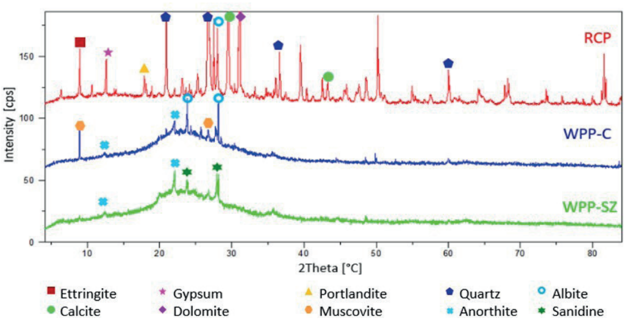


Fig. 4 X-ray diffraction patterns of RCP, WPP-C and WPP-SZ

On the other hand, as characterized by Celik et al. [32], above 500 °C, there is no major weight loss in the case of perlites. The dehydration of perlites is divided into three phases. In the first range between 0 °C and 250 °C, the molecular water superficially bound or adsorbed in the pores is released. From 250–550 °C, molecular water from the inner pores is liberated. While in the third temperature range, between 550 °C and 950 °C, hydroxyl groups are released [32]. Generally, the chemically bonded water in perlites ranges between 2–6% [33]. However, it can be seen in Fig. 3 that for both perlite types there is no major mass change above 500 °C showing presence of molecular water in the pores.

3.2 Experimental methods

The effect of RCP and WPPs as possible cement replacements was comprehensively examined. Mortar mixtures used in the study to investigate fresh density, workability, flexural tensile and compressive strength are presented in Table 3. Mixtures were designed according to MSZ EN 196-1 requirements where the cement, sand and water

Table 3 Mortar mixtures used for the investigation

	Cement [g]	RCP [g]	WPP-C [g]	WPP-SZ [g]	Sand [g]	Water [g]
REF	450	-	-	-	1350	225
RCP15	382.5	67.5	-	-	1350	225
RCP30	315	135	-	-	1350	225
RCP45	247.5	202.5	-	-	1350	225
WPP-C15	382.5	-	67.5	-	1350	225
WPP-C30	315	-	135	-	1350	225
WPP-C45	247.5	-	202.5	-	1350	225
WPP-SZ15	382.5	-	-	67.5	1350	225
WPP-SZ30	315	-	-	135	1350	225
WPP-SZ45	247.5	-	-	202.5	1350	225

content are specified to determine cement strength [19]. The water/binder ratio was kept constant at 0.5. The consistency test was also performed on the specified mortars by flow table test according to MSZ EN 1015-3 [34]. Three 40 mm × 40 mm × 160 mm prismatic specimens for each mixture were fabricated. The fresh density was measured immediately after the prism specimens' mold had been filled with mortar and compacted. In the hardened state, they were first used for the flexural tensile strength test, and then both halves of each specimen were used for the compressive strength test (resulting in six specimens per mixture) [19]. The age of the specimens was 1, 3, 7, 28 and 56 days. All specimens were stored under water at 20 ± 2 °C, except for 56 days, taken out at 28 days to be kept in a temperature and humidity-controlled climatic room. Three replacement ratios for each SCM were investigated as 15, 30 and 45 m%. Moreover, using the SEM, the effect of SCMs on the microstructure of cementitious materials and possible pozzolanic activity was investigated.

For further investigation of selected SCMs' effect on fresh properties of cementitious materials, water demand was examined according to MSZ EN 196-3. Vicat apparatus was used to determine the standard consistency first by mixing 500 g of cement and different water contents until the distance between plunger and base-plate was 6 ± 2 mm. This water content was accepted as one required for standard consistency [22]. The same procedure was followed for the blended cements with 15, 30 and 45% replacement.

4 Results and discussion

4.1 Flexural tensile strength

In Fig. 5, flexural tensile strength results of the mortar samples with the incorporation of the RCP, WPP-C or WPP-SZ are presented. From the results, we can conclude that the flexural tensile strength of the reference for all ages was not reached by the mortars incorporating SCMs, except for the WPP-SZ15 mixture at 28 and 56 days of age. With the increase of the replacement ratio in the case of all SCMs, a decrease in the results was visible. However, there is no definite trend based on the type of SCM used. If we consider the strength activity index (SAI) as a percentage ratio between the strength of investigated mixture and reference, we could conclude that at an early age period (from 1–7 days), there was no overall visible trend of increase in the SAI with age. In this case, the strength of mortar samples mainly depended on the filler effect of SCMs [35]. The inert mineral admixtures contribute to the early age degrees of cement hydration by two main physical effects, i.e., dilution effect and heterogeneous nucleation. The dilution effect decreases the total amount of hydrates without significantly changing the degree of hydration. In comparison, heterogeneous nucleation leads to excess hydrates at a given time and for a given amount of cement. Heterogeneous nucleation is increased with the fineness of the SCM. Even though the heterogeneous nucleation effect increases with the fineness, there is an optimal replacement rate [36].

Even for 28 days of age, RCP inclusion had a more positive effect, with values exceeding WPP-C's for all replacement ratios. The SAI for RCP ranged at this age between about 55–87%, while in the case of WPP-C from about 46–86%. Additionally, WPP-SZ's (higher SSA than WPP-C) values were from about 68–100%. Although pozzolanic activity might be visible, especially for WPP-SZ, the filler effect was still pronounced at this age. Furthermore, pozzolanic activity was clearly visible at 56 days age,

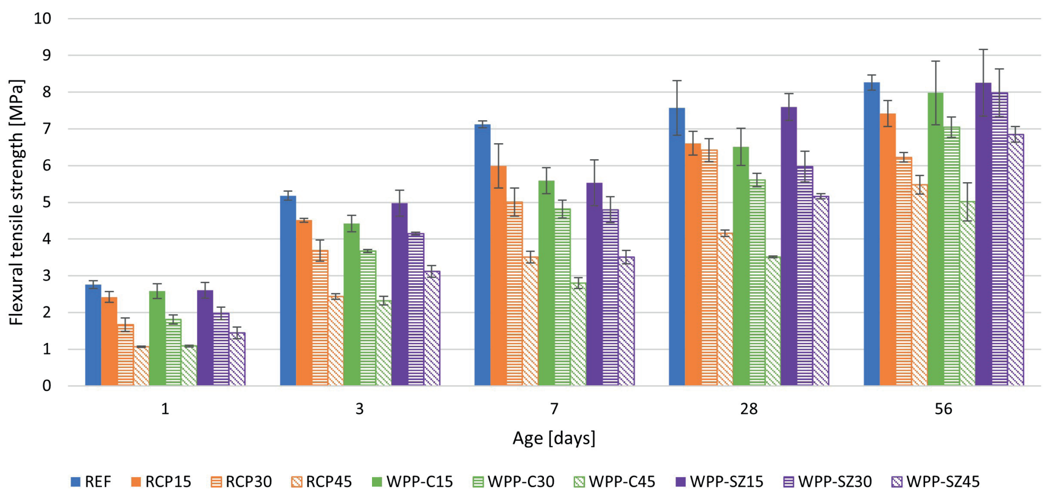


Fig. 5 Flexural tensile strength results of the mortar samples incorporating RCP, WPP-C or WPP-SZ

mainly in the case of WPPs based on the rise in SAI. In the case of 15 and 30% replacement ratios for 56 days of age, the most detrimental effect was corresponding to RCP, which was not that visible in other ages. This can be attributed to the higher pozzolanic activity of the WPPs, leading to better performance of mortars incorporating them. On the other hand, when WPPs were evaluated, the SSA's influence was substantial. While for the WPP-SZ mixture, even with the replacement of 45%, SAI is above 80%, in the case of WPP-C, the values were 97, 85 and 61% for replacement ratios of 15, 30 and 45%, respectively.

4.2 Compressive strength

The compressive strength results were consistent with the flexural tensile strength. The trend for all ages was mainly that compressive strength reduced for all of the SCMs with the increase in the replacement ratio (Fig. 6). Again, it can be concluded that the filler effect is more pronounced for the early-age strength development. Although the pozzolanic effect of both WPPs can be recognized at the age of 56 days, it is more influential in the case of WPP-SZ. Considering the 45% replacement ratio, even at 56 days of age, the WPP-C mixture's results are lower than those including RCP. This can be explained by the SSA of WPP-C, which is lower than half of both the used cement and RCP. For cementitious materials containing pozzolanic materials, strength results are influenced by three pillars, namely the hydration effect of cement, pozzolanic and filler effect [35]. Hence, the filler effect is increased by smaller particles generating denser microstructure and raising overall strength. The beneficial influence of decreasing particle size of the reactive powders was visible in the case of WPPs, where WPP-SZ has a substantially smaller size than any other powder used in the mortars (including cement). Moreover, when compared to WPP-C, which was the powder of the same source but with different SSA, we can see that sometimes large particle size can hinder the pozzolanic effect, as in the case of the 45% replacement ratio.

In order to further evaluate above mentioned three pillars contributing to the strength of the mortar mixtures, the strength development corresponding to the hydration effect of cement multiplying the reference results by the respective percentage amount of cement in the mixtures could be examined. This would be presented in Fig. 7 as cement hydration compressive strength (*fch*). This value can be compared with the experimental results for the respective mixture (*fex*) and evaluated if there was any filler and/or pozzolanic effect. It is essential to mention that reference mixtures had a water/cement ratio of 0.5, while for mixtures containing SCMs, this probably would not be the case. This could be further assessed by examining the water demand. The evaluation only corresponds to 28 (Fig. 7(a)) and 56 days (Fig. 7(b)) of age. We can conclude that for 28 days, just mixtures incorporating WPP-SZ showed insignificantly lower values than theoretical ones. For 56 days' results, the decrease of experimental compared to the theoretical values for all replacement ratios was reduced. Even for WPP-C the reduction was visible from about 11, 23 and 50% for 28 days to about 3, 14 and 39% corresponding to 15, 30 and 45% replacement ratios, respectively. The substantial reduction was not visible in the case of RCP containing mixtures, except for 45% substitution. It is also important to recognize that the reduction in the difference between the values (*fex* and *fch*) mainly increased with the rise in the replacement ratio for all the mixtures. Consequently, 30% and 45% replacement ratios were more detrimental

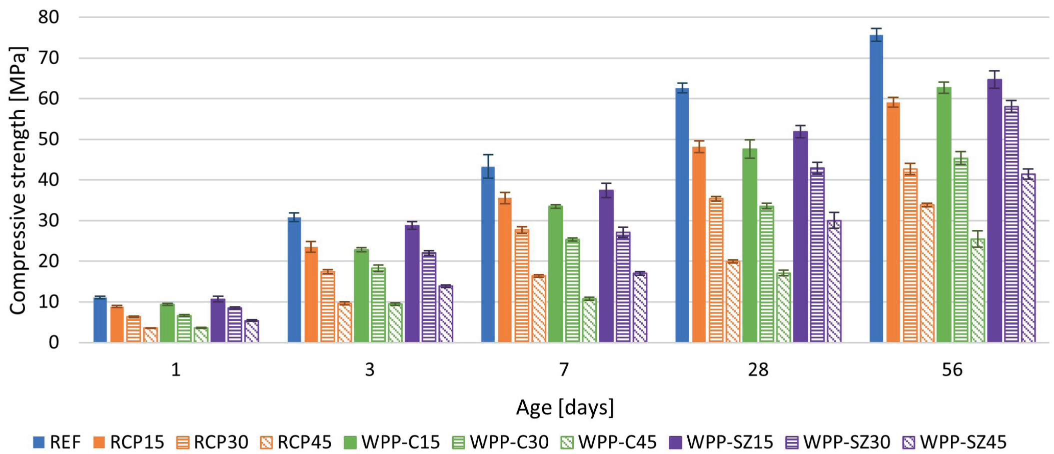
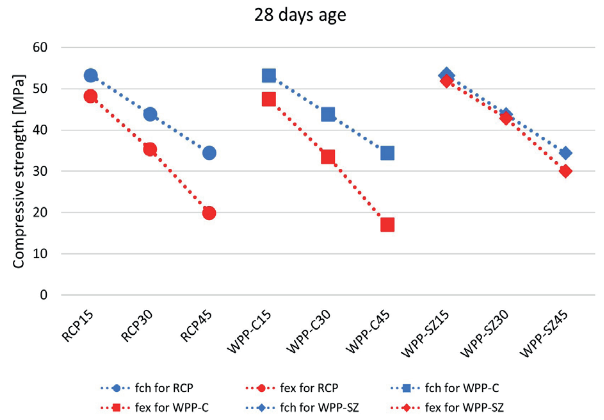
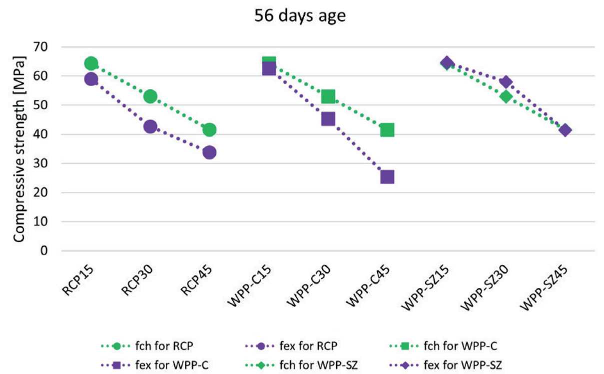


Fig. 6 Compressive strength results of the mortar samples incorporating RCP, WPP-C or WPP-SZ



(a)



(b)

Fig. 7 Comparison of theoretical compressive strength for cement hydration (*fch*) and experimental results (*fex*) for the mortar samples using RCP, WPP-C and WPP-SZ for a. 28 days and b. 56 days age

for powders with both weaker filler effect due to the particle size (WPP-C and RCP) and pozzolanic activity (RCP). RCP seemed like the most inert SCM from the examined powders able to contribute to the strength development mainly through the filler effect.

However, if we consider ASTM C 618 corresponding to standard specification for coal fly ash and raw and calcined natural pozzolan use in concrete, the required SAI at both 7 and 28 days of age is 75% [24]. In Fig. 8 comparison

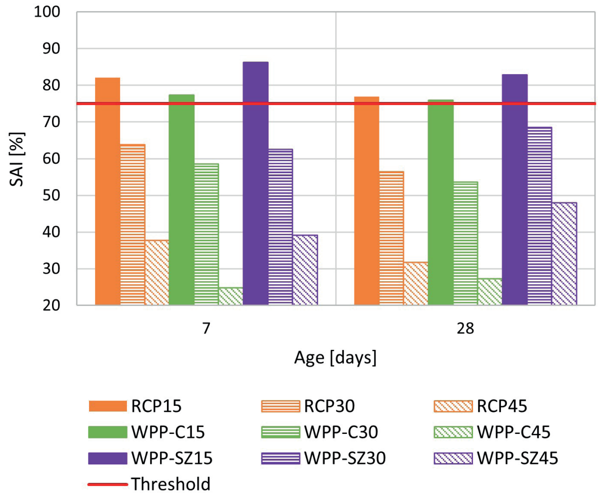
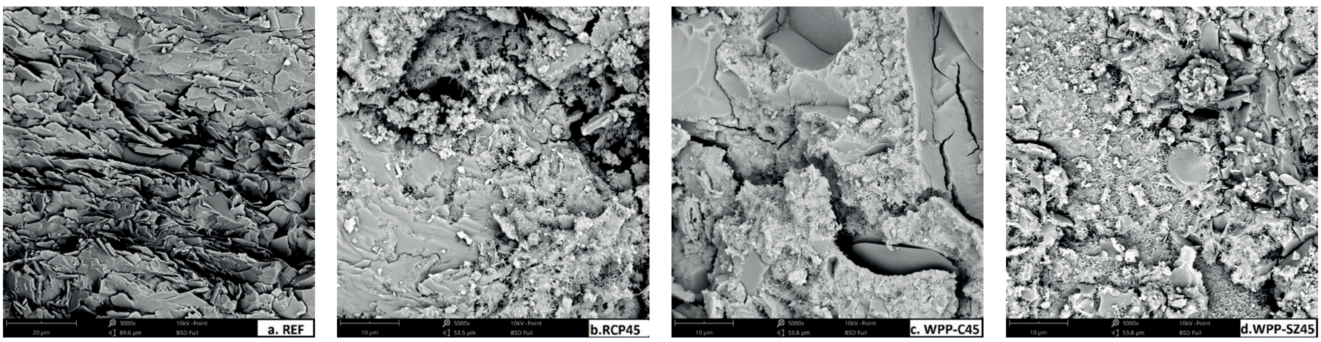


Fig. 8 Comparison of SAI for blended types of cement with the requirement of ASTM C 618

between the results of the mixtures examined and the threshold value required by the code is shown. The lowest value exceeding the threshold corresponded to the WPP-C15 mixture with SAI of just 76% at 28 days of age. It could be concluded that for both ages, only a replacement ratio of 15% met the requirements for all the SCMs. Abed and Nemes [16] also recommended that the usage of WPP as cement replacement should be limited to up to 15% in both natural and recycled aggregate concrete. Hence, better mechanical properties could be expected with the lower dosages of the WPPs than investigated.

4.3 SEM analysis

It was decided to compare the SEM images of reference mortar mixture and mixtures with SCMs of 45% replacement ratio to identify if there is any beneficial change in the microstructure coming from the pozzolanic activity (Fig. 9). In the SEM analysis for the REF mixture, the dense presence of the portlandite ($Ca(OH)_2$) is shown in Fig. 9(a). If the pozzolanic activity were present in the



(a) (b) (c) (d)

Fig. 9 SEM analysis of reference mortar (a) and mortars incorporating 45% substitution by RCP (b), WPP-C (c) and WPP-SZ (d) blended cements investigated, the presence of $Ca(OH)_2$ was expected to be reduced [37]. When SEM image of RCP45 (Fig. 9(b)) is taken into account C-(A)-S-H (hydrated calcium silicates containing or not aluminum) phase, unreacted particles, ettringite and a significant portion of $Ca(OH)_2$ were noticeable. While in the case of WPP-C45 (Fig. 9(c)), a similar trend could be followed, the WPP-SZ45's SEM image (Fig. 9(d)) showed a distinctive presence of C-(A)-S-H with a lower amount of $Ca(OH)_2$. However, the larger availability of fine unreacted particles, probably due to the higher fineness nature of WPP-SZ was detectable. Nevertheless, the densest microstructure of the blended cement mortars was present for WPP-SZ, also attributed to more sound filler effect and pozzolanic activity. There was a significant difference in the microstructure of the samples with the same replacement ratio, demonstrating a positive impact of utilizing WPP-SZ. A high cement replacement ratio can also justify the presence of unreacted particles.

4.4 Fresh density

Fresh density results of the mortar samples with respective replacement ratios for three types of SCMs are presented in Fig. 10. The highest fresh density values corresponded to the WPP-SZ, while the lowest to WPP-C for all replacement ratios. The significance of the fineness of powders was demonstrated. On the other hand, RCP had a higher SG than WPPs, possibly influencing fresh density results. The filler effect can be defined as the proper arrangement of the smaller particles in the cementitious material, increasing the density and, consequently, compressive strength without any chemical reaction [35]. Hence, these aspects could explain the more favorable early age strength results of mortars incorporating RCP than WPP-C. The relationship between fresh density and strength development for blended cements is demonstrated in Fig. 11 with the high correlation coefficients. This shows the pronounced filler effect for the inclusion of investigated SCMs.

4.5 Slump

Generally, the flow behavior of the blended cements with mineral additives is affected by both the content and particle size distribution [38]. Regarding the slump values, the lowest ones corresponded to the WPP-SZ (Fig. 12). RCP and WPP-C had almost matching results for all the replacement ratios. In this case, the water demand could have a significant influence. WPP-SZ had the smallest particle size, which can lead to higher water demand. WPPs had a relatively smoother surface than RCP (as shown in Fig. 2), so RCP's more irregular microstructure is also expected to be influential. The RCP comprised both cement stone and aggregate crumbs. The presence of cement stone increased porosity and could result in higher water absorption. In the mortar samples, the water/binder ratio was kept constant at 0.5. Hence water demand results of the blended cement pastes for standard consistency are presented in the next section.

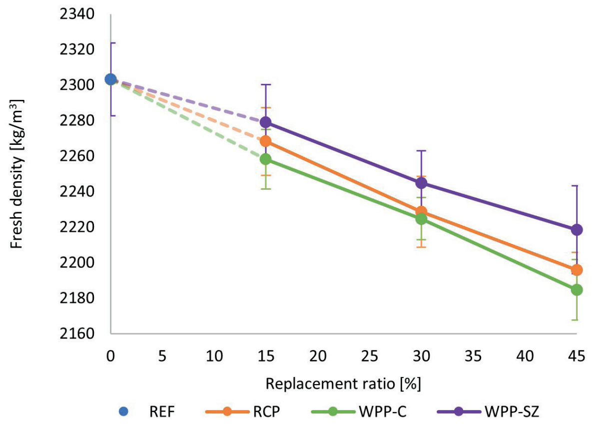


Fig. 10 Fresh density of mortar samples incorporating RCP, WPP-C and WPP-SZ

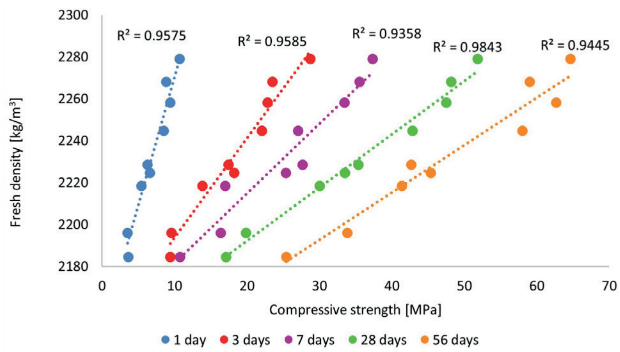


Fig. 11 Correlation between the fresh density of investigated mortar samples and compressive strength

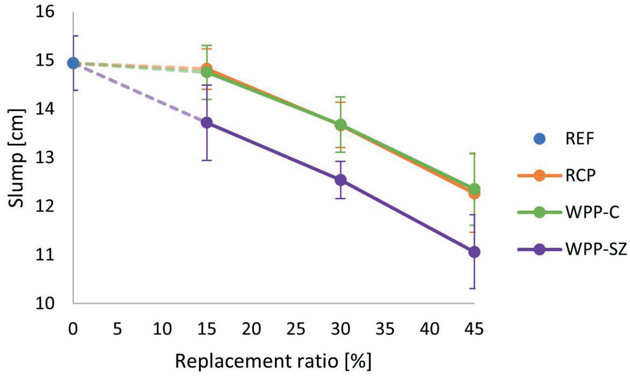


Fig. 12 Slump values of the mortar samples with RCP, WPP-C and WPP-SZ

4.6 Water demand

Water demand for the blended cements with the respective replacement ratios using RCP, WPP-C or WPP-SZ was determined by the water needed to achieve the standard consistency defined in MSZ EN 196-3 [39]. Hence, water demand is expressed as a percentage by mass of the binder (Fig. 13). It can be seen in Fig. 13 that the water demand of the blended cements with WPP-SZ was the highest, and the rise is seen as the replacement ratio increases. This can be attributed to the highest SSA of the WPP-SZ. The trend of increased water demand for blended cements with the rise in SSA explains the behavior of the rest of the samples since WPP-C has the lowest value among the SCMs. This can also be due to the presence of internal and external pores in the respective SCM. While the rise in SSA decreases the number of internal pores, external pores are more pronounced. However, it should be emphasized that the morphology of the particles substantially influences the water demand, which would be more influential in the case of RCP due to its irregular microstructure. It was concluded by previous research that high LOI of SCMs can lead to higher water demand [40]. This can be a significant factor for RCP's results with relatively higher LOI.

5 Conclusions

The utilization of locally available industrial by-products and/or wastes seems like a viable approach to the wider application of sustainable solutions for cementitious materials. It is essential to understand their effect on material properties in addition to their environmental and/or economic benefits. In this study recycled concrete powder (RCP) and waste perlite powders (WPPs) collected from the cyclone (WPP-C) and the baghouse (WPP-SZ) were investigated as supplementary cementitious materials (SCMs). The following conclusions could be made based on the study on the hardened and fresh properties examining the suitability of RCP and WPPs as SCMs:

- The used SCMs differed greatly in both chemical and physical properties. The main differences included density (higher for RCP than WPPs), specific surface area (WPP-SZ>RCP>WPP-C), particle size distribution, the morphology of particles (WPPs have smoother surface), chemical (more heterogeneous for RCP) and phase composition (WPPs demonstrating amorphous character).
- At early age development of flexural tensile and compressive strength, the filler effect was more pronounced for the blended cements. The pozzolanic activity was visible for later ages, especially at 56 days age with mixtures containing WPPs. However, results were still lower for WPP-C with a lower specific surface area for a 45% replacement ratio than for the same mixture containing RCP. It can be concluded that the filler effect was an essential part of the behavior, even at the later ages, for all of the SCMs investigated.
- A replacement ratio of 15% for all the SCMs used could be characterized as not having a substantial adverse effect on the strength results. Although a more detrimental effect for higher replacement ratios (30% and 45%) was present, the utilization of WPP-SZ for such mixtures gave the best results.
- When fresh mortar density was investigated, the highest values corresponded to WPP-SZ, then RCP and the lowest to WPP-C for all replacement ratios, i.e., 15, 30 and 45%. However, any alternative mixture did not reach the fresh density of the reference mortar. This can be attributed to the difference in fineness and specific gravity of the SCMs.
- The fresh density of the mortars containing SCMs showed a high correlation with compressive strength results both for early and later age, which demonstrated the pronounced filler effect.
- The utilization of WPP-SZ resulted in the least benefit on slump values for all replacement ratios examined. Hence, both water absorption and physical properties of SCMs could influence the results. On the other hand, the presence of cement stone for RCP increased the porosity and consequently water absorption capacity. Finally, the slump values were highly influenced by the water demand of SCMs.

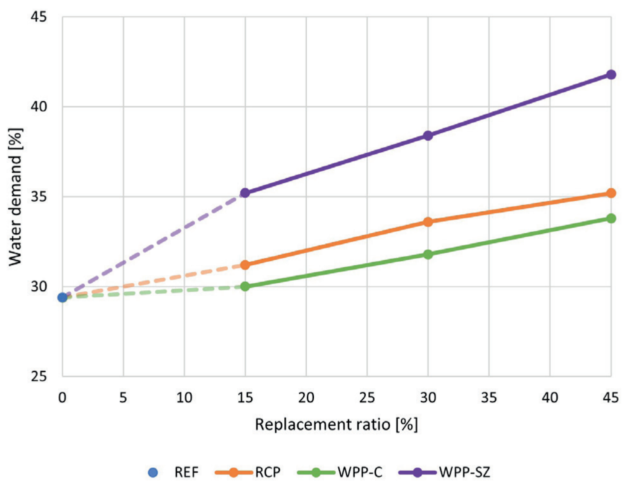


Fig. 13 Water demand of the blended cement pastes utilizing RCP, WPP-C and WPP-SZ

- The water demand for normal consistency differed between various SCMs but was higher than for cement paste excluding SCMs in all cases. Using WPP-SZ resulted in the maximum rise in water demand values for all replacement ratios, followed by RCP and WPP-C. In this case, specific surface area, the morphology of the SCMs as well as loss on ignition have been recognized as influential factors.

Future research should focus on optimizing blended SCMs mixes with the usage of WPPs and/or RCP. This should be done by considering the results from this study on the different behavior of the materials.

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