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Contribution to the Prediction of the Recycling Potential of Recycled Concrete as a Cement Admixture Based on the Compressive Strength of the Parent Concrete

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Abstract

When processing construction and demolition waste, determining the most effective waste management, potential use and recycling method for the identified materials is a key element. To do this, it is necessary not only to determine the type of materials, but also knowledge which aspects of the quality of the original materials are relevant for recycling and the ability to determine the values of these parameters as easily and quickly as possible, directly during demolition activities, is highlighted as an effective tool. This paper, intended as a case study, focuses on the evaluation of the effect of finely ground parent concrete as a cement component, the main objective being to find out whether the differentiation of the quality of the parent concrete, by compressive strength, plays a significant role. The parent concrete, the powder prepared from it, and the new standard mortar mixes, were analysed to obtain a comprehensive picture of the possibility of predicting the properties of the mixes based on the strength of the parent concrete. In general, no clear effect of the parent concrete strength on the flexural strength, compressive strength, water absorption, and ultrasonic pulse velocity values of the new generation mortar was observed. However, finely ground recycled concrete have shown a nice potential to be incorporated in Portland fine-grain cements, reaching strength classes 32.5 and 42.5. Care and precise verification require a 25% replacement, especially in the case of low strength parent concrete.

Keywords Parent concrete, Recycled concrete powder, Cement replacement, Compressive strength

1 Introduction

The demolition of structures increasingly (and to varying degrees in different countries) requires that the waste generated is managed as efficiently as possible. To this end, different procedures are in place for identifying materials in structures, designing further processing streams, and possibly reusing or recycling the waste, which is more or less covered by legislation. Under the Waste Framework Directive (EU, 2018), each EU member state is obliged to take measures to introduce selective demolition to the greatest extent

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possible, with the aim of safely handling hazardous substances and facilitating reuse and recycling, while ensuring the establishment of sorting systems for construction and demolition waste (C&DW). In order to meet the objective, there is a need to focus on a more consistent application of the waste recovery hierarchy, i.e., an increase in the rate of reuse, as well as increasing more valuable ways of recycling materials, but mainly concrete, than is currently the case.

One of the tools for effective management of C&DW, recommended by European Commission, is Pre-Demolition Audit (European Commission, 2018). Its task is to identify and give recommendations on the possibilities of reuse and recycling of materials arising in the process of demolition or renovation, thus contributing to a lower rate of landfilling. The role of audit before demolition is increasingly important, especially when it comes to planning demolition projects and providing information contributing to sustainability and should be a part of the specifications for tenders. Although pre-demolition audits are not yet mandatory for all, they are increasingly being promoted as there is a growing demand for an accurate determination of environmental benefits in relation to the application of circular economy principles. For example, it is included within the BREEAM scheme (BREEAM International New Construction, 2021) as part of the building sustainability assessment process to enable project holders to gain credits for the environmental management of demolition waste.

The point of the audit that we would like to highlight is the auditor's task to determine the most effective further waste management, potential use and recycling method for the identified materials. To do this, it is necessary not only to determine the type of materials but also, where possible, their quality. As for a detailed analysis of the building and the products and materials it contains, ideally, this will be informed by an existing documentation research. The extent of the research is typically decided by the auditor, but the minimum requirement is to study technical drawings and material inventory from the design documentation or any more recent documentation of the building or infrastructure (Wahlström et al., 2019). However, the basic part of the audit is a field survey, which, mainly in case of old buildings, when there is no documentation about the object, is a must. A range of methods for determining the types of materials in the construction comes into play, e.g., portable XRF, IR spectrometers, 3D scanners, as well as manual checklists supported by different national guidance documents with information on the period of use of certain materials. Many of these methods are used to distinguish between materials, but, within a specific group of materials, these are also used to describe their quality.

Concrete structures intended for demolition have—by the very nature of concrete as a material—a considerable variability of properties. This is due to a number of factors such as the composition of the original concrete, the age of the structure, the conditions to which it has been subjected during its service life (Liu et al., 2016; Naderi & Kaboudan, 2021; Pani et al., 2020). For deciding on the waste management and design of recycling in terms of pre-demolition auditing, it is necessary:

- to know which quality aspects of the original concrete are relevant for recycling; and.
- to be able to determine the values of these parameters as easily and quickly as possible, directly during the audit.

These aspects of the pre-demolition audit are still in process and studies are needed to set up the activities to determine how much the quality of the original concrete affects the properties of the new concrete. In fact, several studies have shown that the strength of the parent concrete, from which the recycled aggregate is obtained, influences the strength of the new concrete. Specifically, concrete using recycled aggregates obtained from high-strength concrete has superior mechanical properties and chloride resistance, compared to concrete using recycled aggregates from normal-strength concrete (Kou & Poon, 2015). Similarly, concrete made from recycled aggregate derived from frost-resistant concrete, such as air-entrained concrete, has been shown to exhibit better freeze–thaw resistance (Liu et al., 2016). These effects are due to the characteristics of recycled aggregates generally having higher density and lower water absorption obtained from high-quality concrete (Akbarnezhad et al., 2013; Kim, 2022). The relationship between the quality of recycled aggregates and the properties of the concrete containing them is well established (Choi et al., 2016; Mardani et al., 2024).

However, previous studies investigating the relationship between the properties of the parent concrete and those of the new concrete have focused solely on aggregates obtained from the parent concrete. To achieve zero waste from concrete waste and reduce dependence on cement for sustainable concrete, the utilisation of recycled concrete powder (RCP) generated from the recycling process of concrete waste should be considered (Kim et al., 2023). In general, using RCP as a cement replacement reduces the performance of cementitious materials due to low reactivity of RCP and dilution effect caused by RCP. Therefore, high-volume use of RCP in its original form is not desirable from a performance perspective, and some studies have reported the acceptable replacement rate of RCP to be 30% (Ma et al., 2020; Tang et al., 2020; Xiao et al., 2018). To overcome these drawbacks, investigations into the efficient utilization of RCP have been conducted. Various methods, including thermal, chemical, and mechanical treatments, as well as carbonation, have been reported to enhance the reactivity of RCP (Kim & Jang, 2024; Vashistha et al., 2022). Notably, promising results have been observed with the use of 40% RP combined with thermal treatment and mechanical milling, showing only about a 7.8% reduction in 28-day compressive strength compared to the control group with no RCP (Vashistha et al., 2023a). Furthermore, it has been reported that incorporating 10% silica fume allows for the use of 50% of this thermally mechanically activated RCP, achieving higher 28-day compressive strength than the control group, while also halving CO_2 emissions (Vashistha et al., 2023b).

Therefore, this study, intended as a case study, aims to evaluate the effect of powdery-grained parent concrete as a cementitious component, with the main objective being to determine whether the differentiation of parent concrete quality by compressive strength plays a significant role. Determining the compressive strength of existing structures is one of the less demanding tasks, either destructively when greater accuracy is required (using cylindrical cores), but non-destructive determination using a hardness tester is faster and still sufficient. The auditor would, thus, be able to very quickly recommend an effective method of recycling and direct other waste flows to the final processor. For this case study, a 60-year-old dam was chosen as a model building for the design of a recycling method after possible demolition, from which, real concrete samples (cores) were taken for reconstruction work. In the case of a demolition audit, the same procedure can be used to characterise the quality of concrete, or strength data can be obtained by non-destructive methods. The hardness method provides quick and easy support for the selective demolition of massive concrete structures and obtaining graded material of defined quality. Core samples were obtained from different parts of the structure. Ground parent concrete was tested as a binding component, while two aspects were respected during the design of the composition: a qualitative point of view (strength of the original concrete) and a quantitative point of view (percentage replacement of cement. The parent concrete, the powder prepared from it, and the new standard mortar mixes, were analysed by several methods to obtain a comprehensive picture of the possibility of predicting the properties of the mixes based on the strength of the parent concrete. The results are also discussed in terms of the time evolution of properties as well as the potential of RCP to formulate modern types of Portland recycled cements according to EN 197–6 (2023) Cement—Part 6: Cement with recycled building materials, with which there is yet little experience.

2 Materials and Methods

2.1 Materials

Recycled concrete powder (RCP) for partial replacement of cement was obtained from several core samples of a concrete dam in Slovakia, which has been in use for about 60 years. To study the effect of parent concrete strength on the recycling of the concrete waste as a cement replacement, the sample cores (Fig. 1a) were classified into three groups based on their compressive strength determined by the standard destructive test: low-strength concrete in the range of 20–25 MPa (RCP-L); medium strength concrete in the range of 30–35 MPa (RCP-M);

a) b) c)

Fig. 1 Illustration of RCP materials in the sequence from **a** parent concrete samples, **b** intermediate crushing step, to **c** the new mortar samples

Table 1 Chemical composition of cementitious binders

Type	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	K_2O	SO_3	TiO_2	MnO
Cement	64.06	19.93	4.35	4.95	2.87	0.31	2.45	0.25	0.46
RCP-L	29.83	47.51	5.69	2.97	1.99	0.99	1.04	0.21	0.14
RCP-M	28.41	46.32	6.35	3.40	2.00	1.10	0.93	0.21	0.17
RCP-H	26.64	42.43	5.13	3.13	1.58	0.79	0.90	0.18	0.14

Table 2 Particle size distribution of cementitious binders (μm)

Type	D10	D50	D90
Cement	1.928	9.797	30.362
RCP-L	3.807	36.941	113.585
RCP-M	3.499	32.650	101.477
RCP-H	6.063	58.352	145.407

high-strength concrete in the range of 40–45 MPa (RCP-H). Afterwards, to obtain RCP from the concrete cores, several cycles of crushing were conducted using a laboratory jaw crusher, by gradually reducing the gap between the jaws of the crusher: the first crushing removed particles larger than 4 mm that could potentially be used as coarse aggregate (Fig. 1b). The second crushing removed particles larger than 0.5 mm. The remaining particles were repeatedly crushed and sieved to collect particles smaller than 0.125 mm and used as a partial replacement for cement to produce new mortar samples (Fig. 1c).

An ordinary Portland cement (CEM I 52.5 R), conforming to the European Standard, EN 197–1, was employed as the binding agent. Standardized sand, conforming to EN 196–1, was used to prepare standard mortar mixtures.

To characterise the powdery input materials (cement and RCP-L, M, H), following three methods and relevant parameters were determined:

- X-ray fluorescence analyser (SPECTRO IQII, AMETEK, Germany), to determine the chemical composition (Tab. 1)
- laser granulometer (Mastersizer 2000, Malvern Instruments Ltd, UK), to determine the particle size distribution (Tab. 2 and Fig. 2)
- thermo-gravimetric analyser TG–DTA/DSC (STA 449 F3; NETZSCH, Germany), to determine the thermal stability of materials. Tab. 3 presents mass losses representing the decomposition of the CSH phase, portlandite and carbonates. Fig. 3 show DSC and TG curves of RCPs, respectively.

From a cumulative view of the properties of the input materials, it can be noted that the best quality RCP specimen in terms of compressive strength (RCP-H) is confirmed also by TG analysis. In Fig. 3, it is possible to see the peaks attributed to the decomposition of typical

Table 3 Mass losses of RCPs, determined by TG analysis

Type	Mass loss (%)		
	70–400 °C (CSH)	400–500 °C (portlandit)	600–900 °C (carbonates)
RCP-L	6.67	1.28	11.22
RCP-M	4.80	1.19	11.26
RCP-H	8.65	1.38	8.65

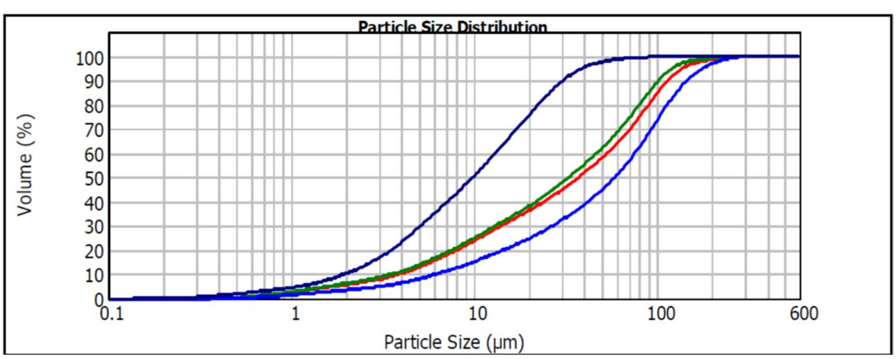

Fig. 2 Particle size distribution of cementitious materials, namely: cement (black), RCP-L (red), RCP-M (green), and RCP-H (blue)

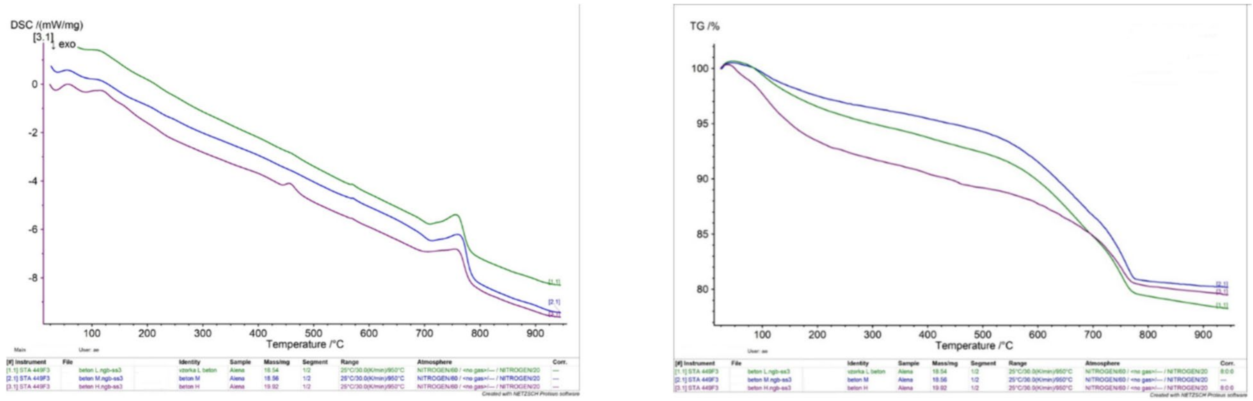

Fig. 3 DSC and TG curves of RCPs

hydration products of concretes (CSH phase and portlandite), the polymorphic transformation of quartz, as well as the peak attributed to the decomposition of carbonates. This peak indicates an ongoing carbonation process in the concrete materials. Based on the area of the carbonate decomposition peak, it can be concluded that parent concrete M contained the highest amount of carbonate, indicating that it was the most carbonation damaged compared to the other two concretes. On the contrary, parent concrete H contained the lowest amount of carbonates and, therefore, showed the lowest degree of carbonation, which is supported by the fact that the peak of portlandite in the 400–500 °C interval was also present in concrete H (as seen in the DSC curve of concrete H—Fig. 3). The assumption of the highest quality of concrete H is also supported by the highest weight loss of 8.65% in the temperature range 70–400 °C, which is attributed to the decomposition of the CSH phase. The parent concrete sample M appears to have the worst functional parameters in terms of the lowest CSH phase content and the highest degree of carbonation, while sample H appears to be the most stable in this respect. (Table 3 and Fig. 3). On the other hand, a likely consequence of this higher strength and overall quality of parent concrete H was the coarser grain size of the RCP-H powder (Fig. 2), which was prepared by the same process as the other two (as described above). This fact is subsequently echoed in the results obtained, as will be discussed below.

2.2 Preparation of RCP Mortars

The preparation of RCP-mortar samples, including the mix compositions, was carried out according to *EN 196–1: Methods of testing cement—Part 1: Determination of strength*. The mix proportions of 10 groups of mortars were prepared, including the control one without RCP, and 3 groups of 3 mixtures according to

Table 4 Mix proportions of mortars (g)

ID	Water	Cement	RCP-L	Sand
Control	225	450	0	1350
L5	225	427.5	22.5	1350
L15	225	382.5	67.5	1350
L25	225	337.5	112.5	1350

the strength of the parent concrete (L, M, H) and the replacement rates of cement by RCP (5%, 15%, and 25%). Table 4 shows the principle of mix compositions for “L” group, namely, L5, L15 and L25. Sample groups M and H were prepared with the same composition rule. Each mixture was named by the strength of the parent concrete and the replacement rate of the RCP. For example, H25 describes a mixture containing 25% RCP obtained from high strength concrete. The mentioned binders were designed in accordance with the relatively new standard EN 197–6 ‘*Cement—Part 6: Cement with recycled building materials*’ (EN197–6, 2023), according to which, they fall into the following types: Portland fine-grained recycled cement CEM II/A-F (5% and 15% of replacement), and CEM II/B-F (25% replacement). The standard defines finely ground recycled concrete as mostly non-reactive. Residual hydraulic or pozzolanic reactivity is possible but does not contribute significantly to the reactivity of the cement. These types of cement allow the specifier and the user to contribute to the sustainability goals for cement-based constructions and the circular economy and to minimise the use of natural resources in accordance with local production conditions.

After weighing, the materials were mixed in an automatic mixer and cast into 40 mm × 40 mm × 160 mm prismatic moulds. The cast samples were demoulded after 24 h and cured in water at 20 ± 2 °C until testing.

2.3 Methods

Various properties of mortars were tested according to standards.

The fluidity of the mortars in the fresh state was tested in a flow table according to EN 1015–3 (EN, 1015–3, 1999). The mixture was dropped 15 times on the flow table, and the diameters were measured in two directions at right angles.

For the hardened properties of the mortars, the strengths, water absorption, and ultrasonic pulse velocity (UPV) were measured at ages of 28, 90, and 180 days.

Flexural and compressive strengths were tested according to the procedures specified in EN 196–1 (EN, 2018). The flexural strength was performed on prism specimen, and the compressive strength was conducted on the specimen split in two, by the flexural strength test.

Water absorption was determined according to KS F4004 (KS, 2018) using the difference between the saturated mass (immersed in water until the test date) and the dry mass (heated at 105 °C until there was no change in mass) of the specimen.

The UPV, a type of non-destructive testing, was measured by placing an ultrasonic receiver and transmitter at the longitudinal ends of the prism specimen. To determine whether the measured UPV could provide acceptable predictions, it was utilised for correlation analysis with other properties.

Finally, an X-ray diffractometer (D2 Phaser, Bruker AXS, Germany) was used to identify the mineralogical composition of the mortars and compare them. For the test, hardened samples were grinded to obtain powdery form.

For the hardened properties, three specimens per series were tested and the average values are presented, including the standard deviation.

3 Results and Discussion

3.1 Flow Table

The test results of the flow table for the prepared mortar mixtures are shown in Fig. 4. The flow of the standard mortar was 171 mm and that of the recycled mortar ranged from 151 mm (M25) to 174 mm (M5). As the replacement rate of cement by RCP increased, a clear decrease in the flow of the mixture was observed. This is due to the increased water demand for flow due to the coarser and more porous RCP particles than cement (Jiang et al., 2022; Kim & Choi, 2012; Kim et al., 2023). The effect of RCP obtained from parent concretes with different strengths on the flow of mortar was not clearly identified. At each replacement rate, the difference in the flows of L, M, and H mixtures did not exceed 10 mm, which indicates that the influence of the parent concrete on the flow of RCP mortar is insignificant.

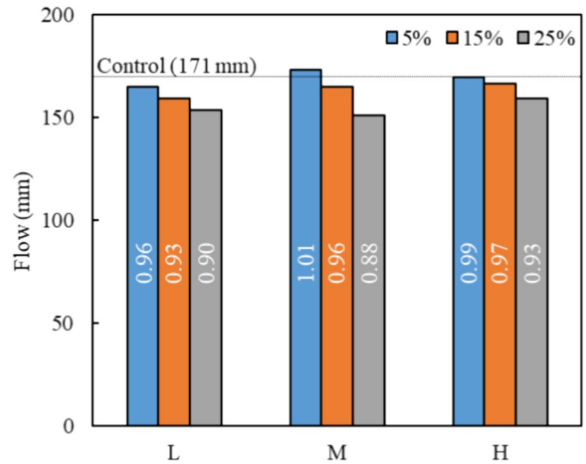

Fig. 4 Flow table test of mortar with and without RCP

3.2 Flexural Strength

The test results of the flexural strength of mortars cured for 28, 90, and 180 days are shown in Fig. 5. Regarding the effect of RCP replacement rate, a gradual decrease in flexural strength was expected with increasing replacement rate, but some irregular results were observed. For example, the 28-day flexural strength of M5 mortar was 6% lower than that of the standard mortar, but M15 mortar showed slightly higher flexural strength than M5 mortar. In addition, the 28-day flexural strength of H15 mortar was reduced by 20% compared to the standard mortar, but the flexural strength of H25 was slightly increased compared to H15. However, from an overall perspective, as the replacement rate by RCP increased, the flexural strength decreased, which is generally consistent with the results of previous studies (Kim et al., 2023).

In general, the flexural strength of the mortars prepared in this study peaked at 90 days of age, but for some samples (L5, L25, and H25), the 90-day strength was lower than the 28-day strength. Specifically, the 180-day flexural strengths of all mortars, except for the L25 sample, were lower than the 90-day flexural strengths, indicating that the use of RCP did not have a favourable effect on long-term development of flexural strength. This behaviour is not only inconsistent with the compressive strength results of this study, but also contradicts a study that stated that extended curing period has a positive effect on the flexural strength of RCP mortars due to the pozzolanic activity and filler effect of RCP (Tang et al., 2020). Although not mainstream, similar results were reported in a study by Topič et al. (Topič et al., 2016). In that study,

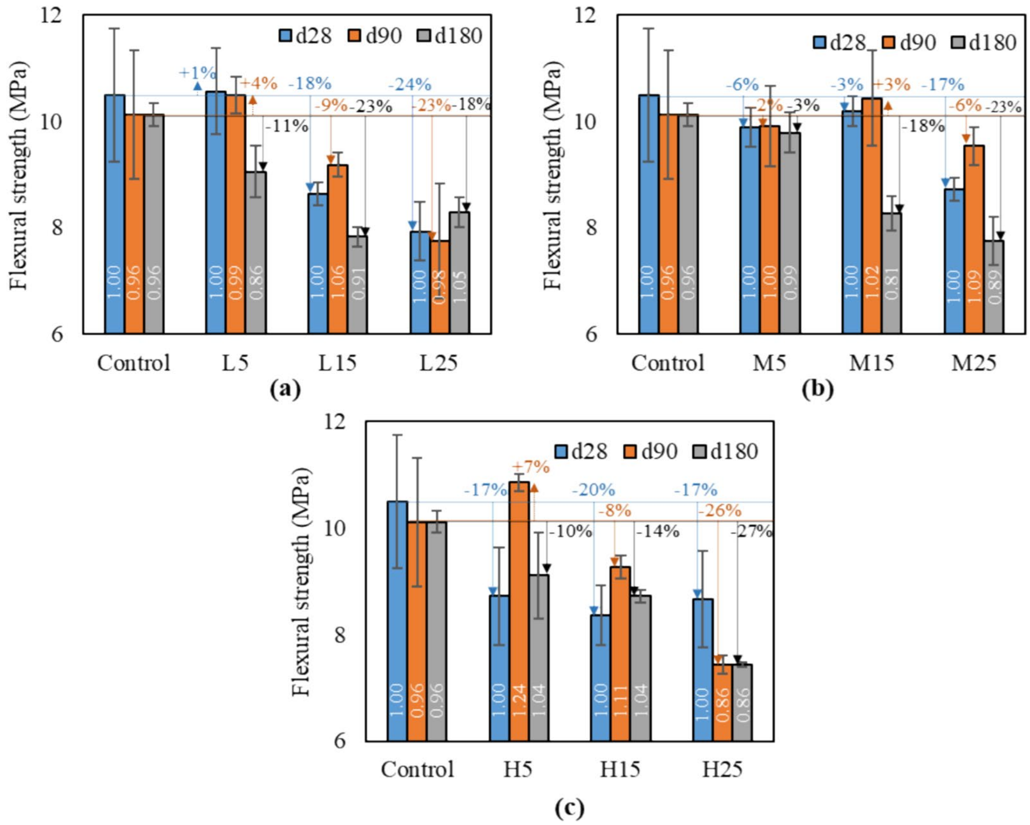

Fig. 5 Flexural strength of mortars: **a** RCP from low strength concrete; **b** RCP from medium strength concrete; **c** RCP from high strength concrete

the long-term flexural strength (287 days) was approximately 11% lower than the 28-day flexural strength, while the compressive strength increased by 96% over the same period, and authors point out that it needs to be further studied and explained.

For here presented study, the authors would like to put forward two views. The first is the assumption of a degradation process just starting at around 180 days (probably leaching of the Portlandite), which is not yet reflected in the compressive strength, as concrete is more effective against this action. This could be confirmed by longer-term observations that would reflect degradation processes for this strength as well. Second, the authors would like to point out for the moment the likelihood of more indicative res3 as well.ults for compressive strength and other properties tested. It may be noted that (as given below), the compressive strength results are more consistent with standard assumptions (e.g., that strength will decrease as the proportion of replacement increases, which is always true for compressive strength but not always true for flexural strength) or based on UPV results, which correlate better with compressive strength than with flexural strength—see Figs. 6, 7. While for flexural strength the R^2 values go from 0.5392 to 0.6872, for compressive strength, they are from 0.8392 to 0.959.

Fig. 8 compares the flexural strength at 28 and 180 days of age. For given replacement rates, the difference between minimum and maximum flexural strengths at 28 days is relatively large, ranging from 0.79 MPa to 1.84 MPa, but this difference stabilised at 180 days in the range of 0.73 MPa to 0.89 MPa, so that the mortars show similar flexural strengths. In line with the compressive strength results, there was no clear observed effect of the strength of the mother concrete on the flexural strength of the next-generation cementitious mixture. In Fig. 8, it can also be noticed that the mortars with the strongest RCP-H are at the lower end of the values compared to mortars L and M. It is assumed that the effect of the larger grain size of RCP-H on its reactivity is more pronounced here than the effect of its strength.

Plotting the maximum and minimum limits of the values obtained for each test batch in the graphs comparing the performance of mortars defined with waste from concrete with different strength classes is given in Fig. 9. In this way, it is possible to visualize whether finely ground parent concrete from more resistant parent concrete tends to generate mortars with better performance.

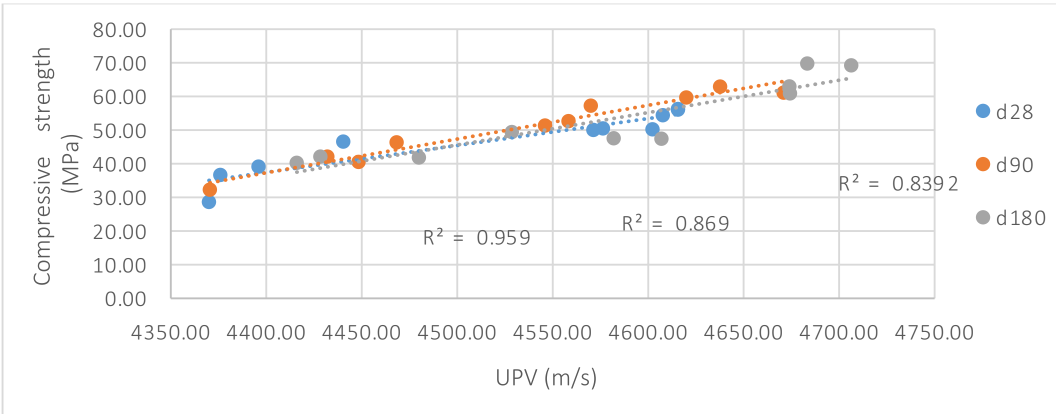

Fig. 6 Relationships between results of UPV and compressive strength

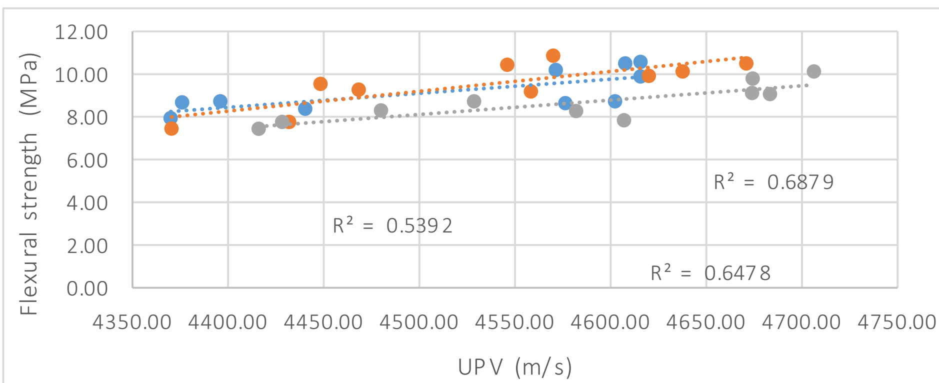

Fig. 7 Relationships between results of UPV and flexural strength

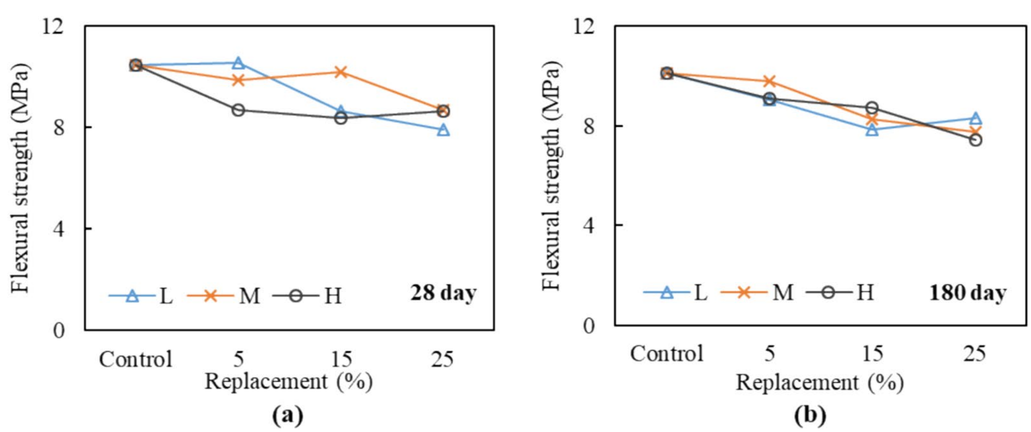

Fig. 8 Flexural strength of L, M and H mortars at 28 days **a** and 180 days **b** according to replacement level

It can be said that the signatures of the individual values are displayed essentially in a single line (with a larger scatter in the L—28-day series, indicating the importance of the replacement level for low-quality parent concrete in short-term horizon), and thus, the influence of the strength class of the parent concrete appears to be marginal.

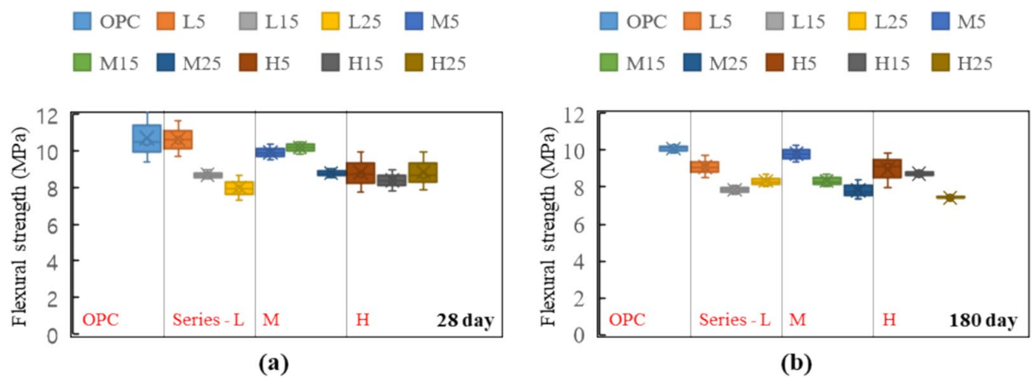

Fig. 9 Flexural strength of L, M and H mortars at 28 days **a** and 180 days **b** according to quality level

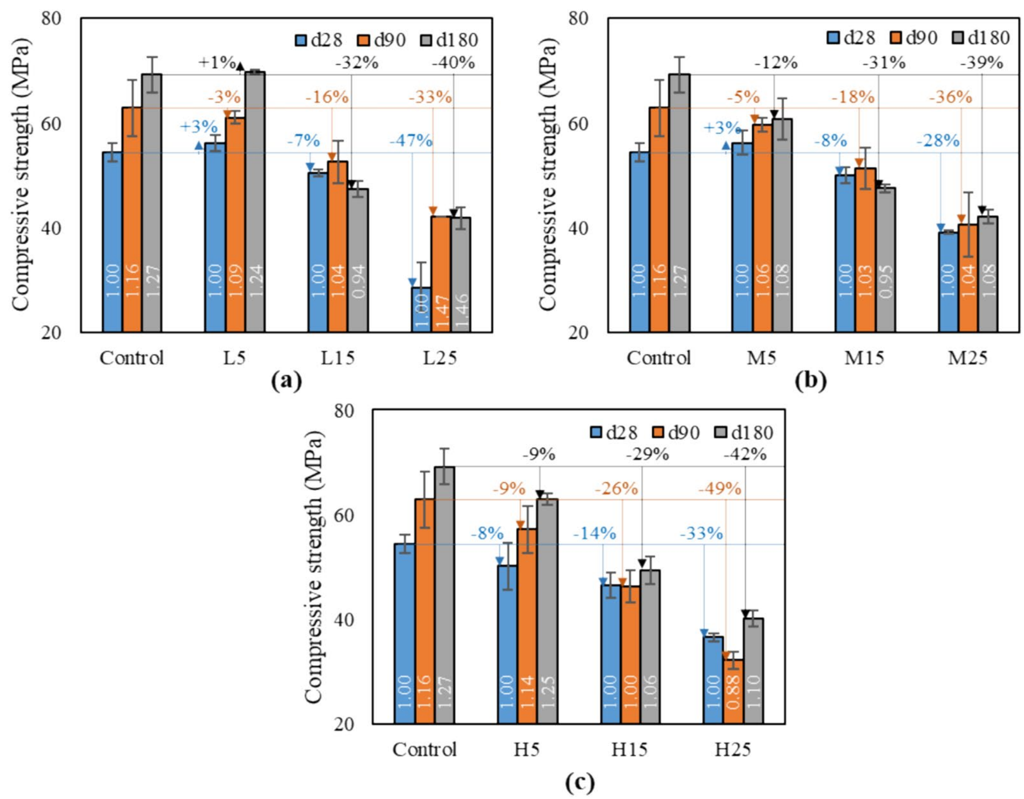

Fig. 10 Compressive strength of mortars: **a** RCP from low strength concrete; **b** RCP from medium strength concrete; **c** RCP from high strength concrete

3.3 Compressive Strength

The test results of the compressive strength of the mortar specimens cured for 28, 90, and 180 days are shown in Fig. 10.

In general, the compressive strength of cementitious mixtures is rapidly developed in the early stages and becomes moderate in the later stages (Corinaldesi et al., 2016; Kotwa, 2019). In addition, in this study, the assumptions about the increase in strength with time are more clearly fulfilled; except for L15 and M15, mortars showed an increase in compressive strength with age. This may be due to a change in the tobermorite content as indicated, e.g., for sample H25 (Fig. 11). The figure shows the XRD recordings for the samples in 28 days and 180 days of curing. In 180 days, there was an increase in tobermorite peak intensity at 50.09° and 29.2° 2theta, representing the CSH phase.

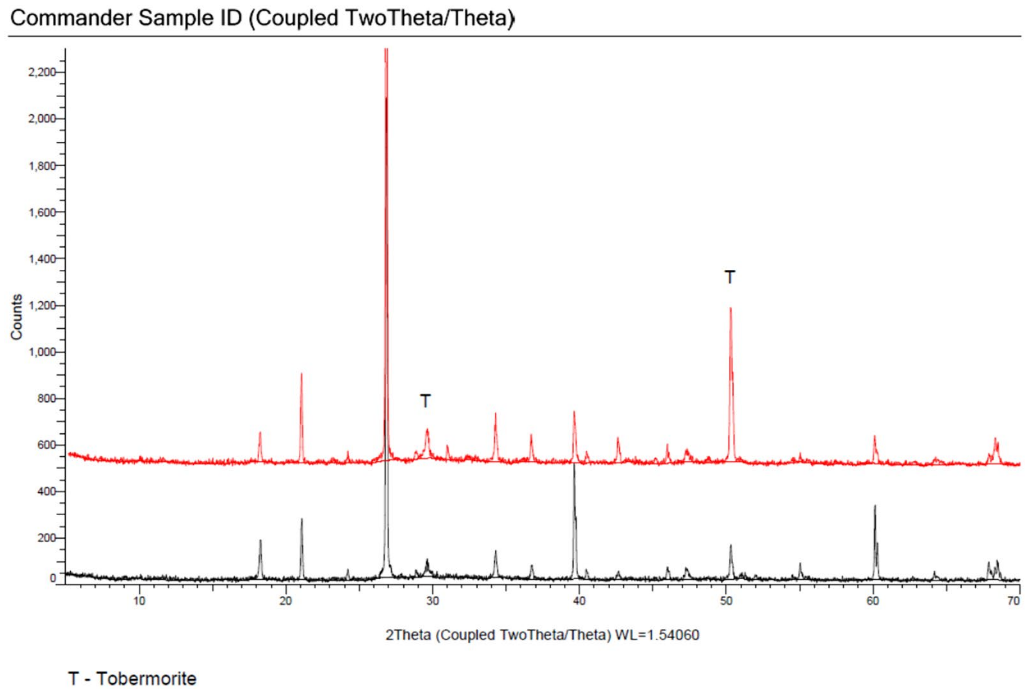

Fig. 11 Comparison of XRD records of H-25 sample in 28 days (black) and 180 days of curing (red) with tobermorite peaks indicated

As is widely recognised, it is a familiar fact that increasing the replacement rate of RCP reduces the hydration rate, subsequently leading to a reduction in the compressive strength of mortar (Kim & Kim, 2023; Kim et al., 2023). However, it is worth noting that the use of RCP, particularly at high-volume replacement, increases the loss of compressive strength over time. Specifically, when compared to a control mortar with the same curing duration, the compressive strength of M5 is 3% higher at 28 days, 5% lower at 90 days, and 12% lower at 180 days. Furthermore, for M15, the 28-day compressive strength is 8% lower, indicating no concerning losses. However, this difference grows significantly to − 18% at 90 days and -31% at 180 days. Similar behaviour can be seen with L samples, where the compressive strength of L5 is 3% higher at 28 days, 3% lower at 90 days, and 1% higher at 180 days. For L15, the loss of compressive strength progressively increases to -7%, -16%, and -32%, at the given ages.

This is associated with reduced strength development in the later stages due to the exhaustion of limited amounts of unhydrated particles in the early stages of hydration (Gao et al., 2022). The finding of a long-term strength disparity between the control mortar and RCP mortar can be of utmost significance in practical application and performance assessment. It indicates that the application of current standards, primarily requiring 28-day strength, may not be adequate for quality assessment of RCP-based mortars.

To investigate the effect of the strength of parent concrete of the RCPs, the 28-day compressive strengths of RCP-L, RCP-M, and RCP-H are presented in Fig. 12a. At replacement rates of 5% and 15%, mortars containing RCP-L and RCP-M show similar strength, while the compressive strength of RCP-H mortar is 8–12% lower than that of RCP-L and RCP-M mortars. With a certain probability, these results can be attributed to the different particle sizes of the RCPs, as shown in Table 2. According to a study conducted by Du et al. (2023), the fine RCP fraction exhibits a higher content of unhydrated phases and aged hydration products, compared to the coarse RCP fraction. In addition, the filling effect of the fine RCP enhances the density and homogeneity of the microstructure within the mixture, consequently improving its strength (Li et al., 2022). Hence, the strength of the mortar with RCP-H, which has a larger particle size, is comparatively lower than that of the others. The results are also supported by a slightly lower content of hydraulic oxides in RCP-H, as presented in Table 1. Similar to flexural strength results, it is assumed that the effect of the larger grain size of RCP-H on its reactivity is more pronounced than the effect of its strength.

Fig. 12b shows the compressive strength at 180 days of age. At given replacement ratios, the difference between

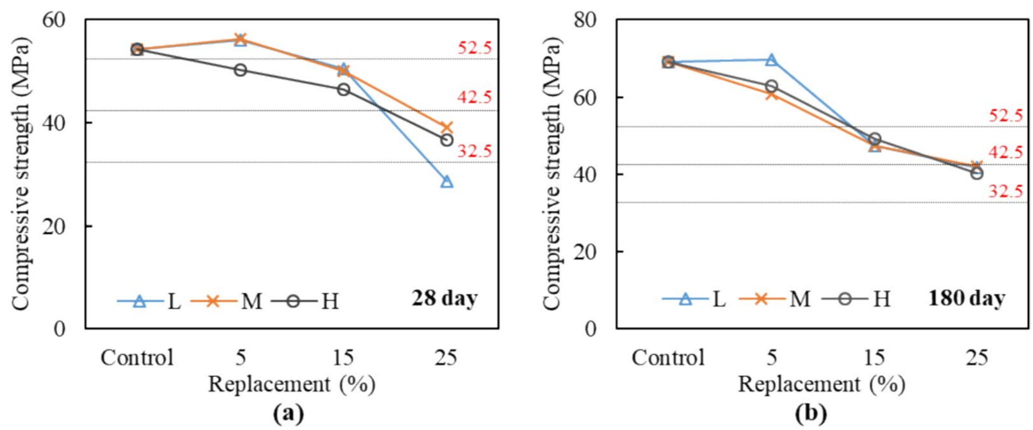

Fig. 12 Compressive strength of L, M and H mortars at 28 days (**a**) and 180 days (**b**) according to replacement level

the minimum and maximum compressive strength stabilises, as is the case for the flexural strength. This is more convincing at higher replacement levels (15% and 25%). At 25% replacement and 180 curing days, the decrease in strength compared to the control specimen is 40% for L, 39% for M, and 42% for H, with strength values of 41.8 MPa, 42.1 MPa and 40.2 MPa, respectively. Therefore, even here, no clear observed effect of the strength of the parent concrete on the compressive strength of the new generation cementitious mix can be deduced. It appears that with increasing replacement ratio and increasing age of the specimens, the strength of the parent concrete becomes less significant.

Similar to flexural strength and according to visualization given in Fig. 13 can be said, that the signatures of the individual values are displayed essentially in a single line (with a larger scatter in the L—28-day series), and thus, the influence of the strength class of the parent concrete appears to be marginal. More important and clearly visible are differences indicating the importance of the replacement level in each strength group of parent concrete.

In addition to the quality of the parent concrete, the results obtained can be discussed in terms of testing specific types of composite cements that contain RCP as admixtures. According to EN 197–1, cement grades can be categorised as 32.5, 42.5, and 52.5 based on their 28-day compressive strength (Fig. 12a). In this study, certain mortars (L5 and M5) exhibited higher strength than the control mortar, meeting the criteria for the 52.5 grade. While the compressive strength decreases as the replacement rate increases, RCP-M and RCP-H satisfy the requirements for the 42.5 and 32.5 grades. For RCP-L, there is a significant decrease in strength observed at 25% replacement rate, which falls below the minimum strength required by the standard. This indicates the need for caution when considering high volume replacement of RCP produced from low-strength concrete. However, looking at the average results of all RCPs after 180 days, it can be noted that although the reductions in compressive strengths compared to the control sample (69 MPa) are 30% (15% replacement) and 40% (25% replacement), the values of 48 MPa and 41 MPa, respectively, allow these replacements to be considered and further tested for use

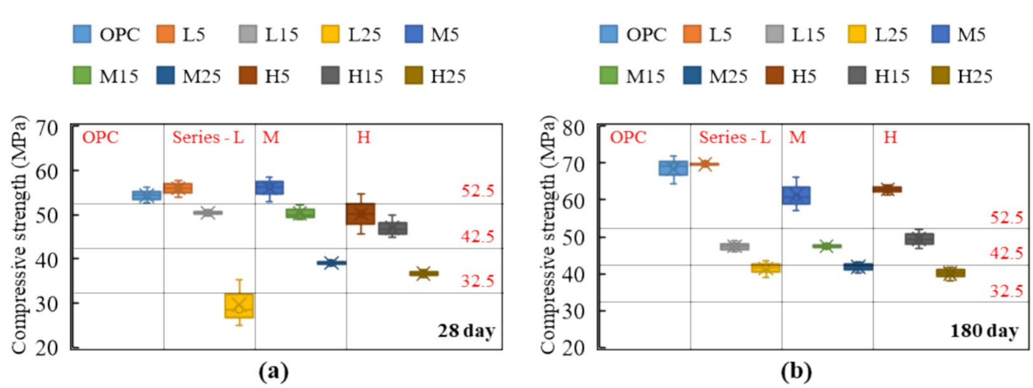

Fig. 13 Compressive strength of L, M and H mortars at 28 days **a** and 180 days **b** according to quality level

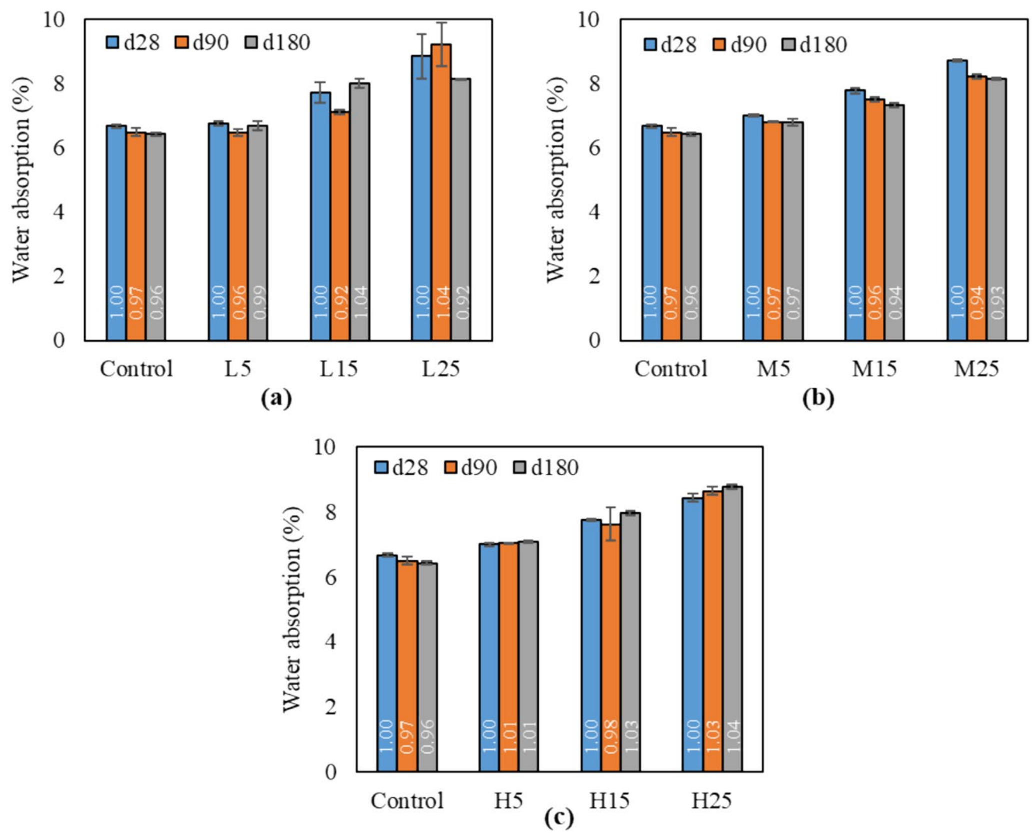

Fig. 14 Water absorption of mortars: **a** RCP from low strength concrete; **b** RCP from medium strength concrete; **c** RCP from high strength concrete

in CEM II/A-F or B-F type of cement according to EN 197–6.

3.4 Water Absorption

The water absorption by immersion of mortar samples is shown in Fig. 14. The replacement rate of RCP played a role in increasing the water absorption of mortar. While the 28-day water absorption of the standard mortars was 6.67%, that of RCP-mortars increased to 6.76%, 7.71% and 8.85% for the L series; 7.00%, 7.77%, and 8.73% for the M series; 7.00%, 7.74%, and 8.42% for the H series, at replacement rates of 5%, 15%, and 25%, respectively. As reported in previous studies (Kim et al., 2023; Sharaky et al., 2021; Wu et al., 2021, 2022), the incorporation of RCP in cementitious materials reduces the formation of hydration products in the cement matrix and makes the microstructure porous, providing more paths for water inflow.

The influence of RCP on the long-term behaviour of water absorption in mortars was not consistently observed. For the L series, water absorption decreased at 90 days and increased again at 180 days for 5% and 15% replacement rates, while the opposite pattern was observed at 25% replacement rate (i.e., increase at 90 days and decrease at 180 days).

Fig. 15 shows water absorption measured at 28 and 180 days. Like the strength test results, the effect of RCP from parent concrete with varying strengths on water absorption could not be conclusively interpreted. For instance, at 5% replacement rate, the 28-day water absorption followed the order of M = H > L. However, at 25%, the order reversed to L > M > H, which reversed again to H > M > L at 180 days. Nevertheless, it is noteworthy that, at the same replacement rate, the difference in water absorption between the L, M, and H series was 0.43% at 28 days and 0.67% at 180 days. Hence, it can be considered that the strength of parent concrete does not have a significant effect. Fig. 16 shows again marginal influence of the strength class of the parent concrete on the water absorption of mortar samples.

The water absorption results also support the consistency of compressive strength results, exhibiting a strong correlation. In Fig. 17, a strong linear relationship with an R^2 value above 0.8 is demonstrated.

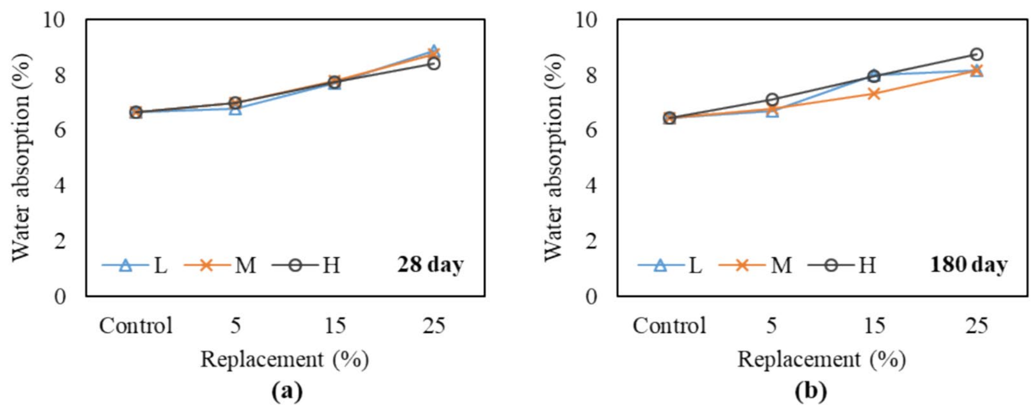

Fig. 15 Water absorption of L, M and H mortars at 28 days (**a**) and 180 days (**b**) according to replacement level

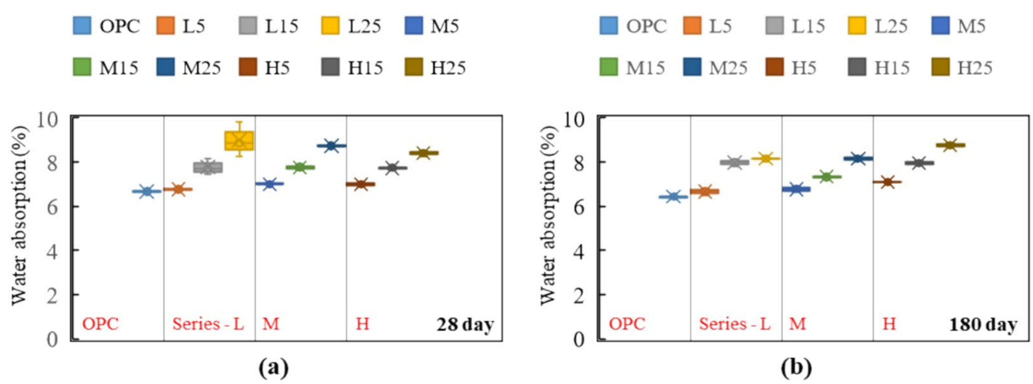

Fig. 16 Water absorption of L, M and H mortars at 28 days (**a**) and 180 days (**b**) according to quality level

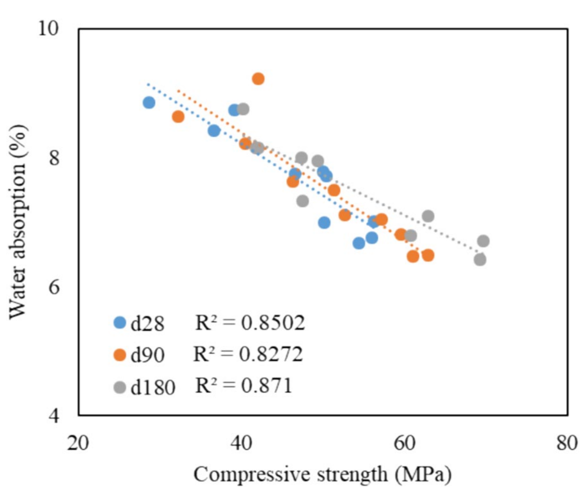

Fig. 17 Relationship between compressive strength and water absorption

3.5 Ultrasonic Pulse Velocity

The UPV results of the mortar samples at 28, 90, and 180 days are shown in Fig. 18. In cementitious materials, higher UPV values often indicate a denser microstructure. With increasing replacement rates, the mixture became more porous and, consequently, the UPV gradually decreased. Using 5% RCP resulted in a UPV reduction of up to 1.5% compared to the reference mortar, while at 15% and 25%, the reduction reached up to 3.8% and 6.2%, respectively. Overall, the UPV showed an upward trend over time, but the increase in 90-day and 180-day UPVs remained within the range of 1–3% of the 28-day UPV.

UPV values are frequently applied to the prediction of various properties of cementitious mixtures. Fig. 19 plots the relationship between UPV, compressive strength, and water absorption, using regression analysis. As expected, the UPV increased with higher compressive strength and lower water absorption in the mortar samples, demonstrating a good linear correlation irrespective of the parent concrete's strength.

3.6 XRD Analysis

The mortars were analysed for mineralogical composition by XRD to confirm or exclude any unexpected element. As expected, all samples showed the presence of the same minerals, such as P (Portlandite), Q (Quarts),

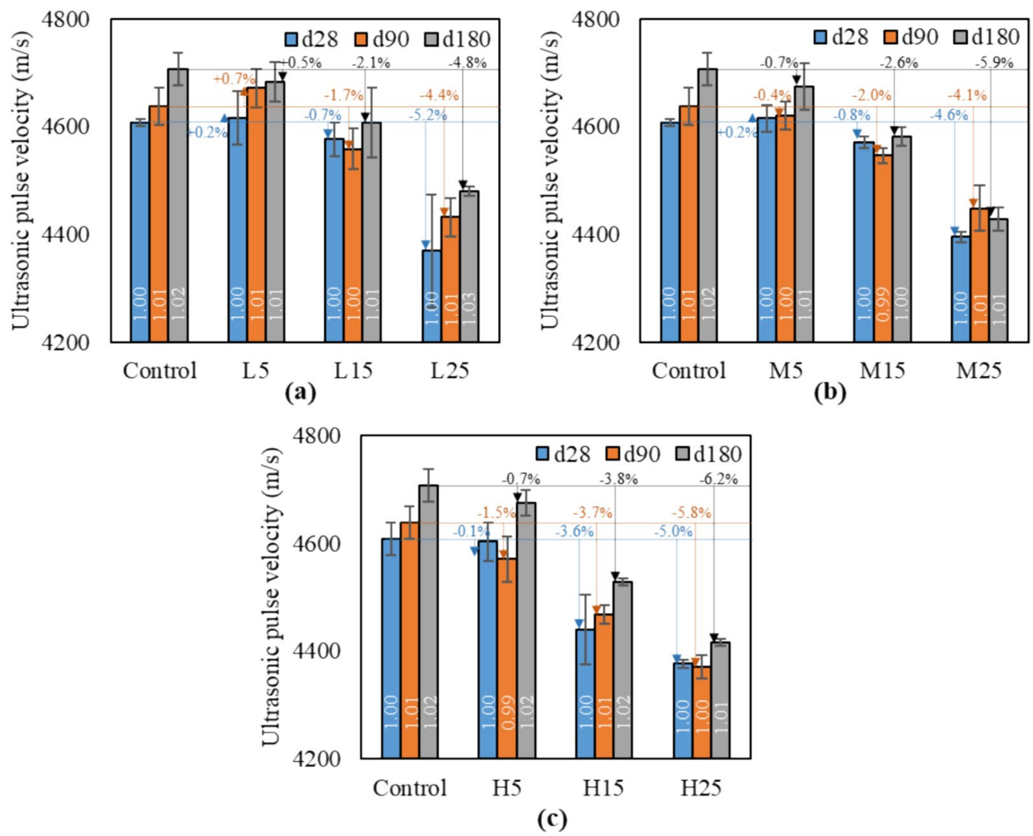

Fig. 18 Ultrasonic pulse velocity of mortars: **a** RCP from low strength concrete; **b** RCP from medium strength concrete; **c** RCP from highstrength concrete

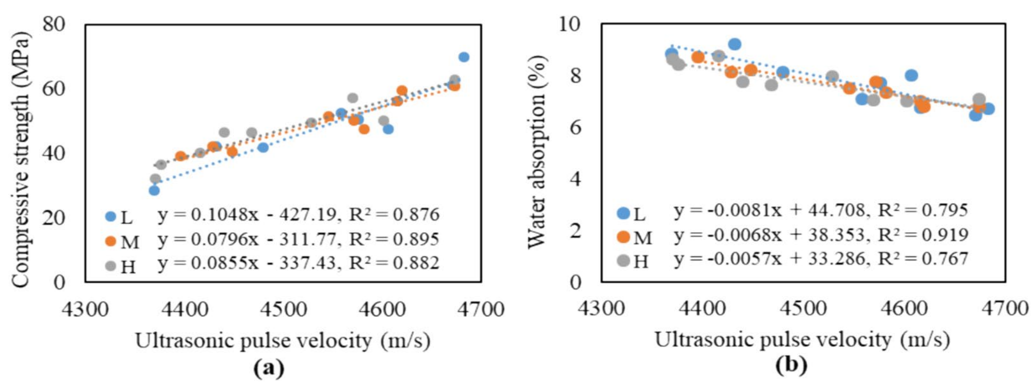

Fig. 19 Relationship between ultrasonic pulse velocity and compressive strength (**a**) and water absorption (**b**)

C (Calcite), CSH (hydration minerals), and some S (sulphate minerals). As an example, a comparison of mortars prepared with high strength RCP (RCP-H), along with a control sample, is shown in Fig. 20. The XRD patterns are essentially the same, indicating the formation of the same hydration products, without the presence of unexpected components.

4 Conclusions

For this case study, concrete samples from a 60-year-old dam were taken from different parts of the structure to obtain the parent concrete material, with different compressive strengths. The samples were divided into three groups of low, medium and high compressive strength and ground into powder form: RCP-L, RCP-M, and

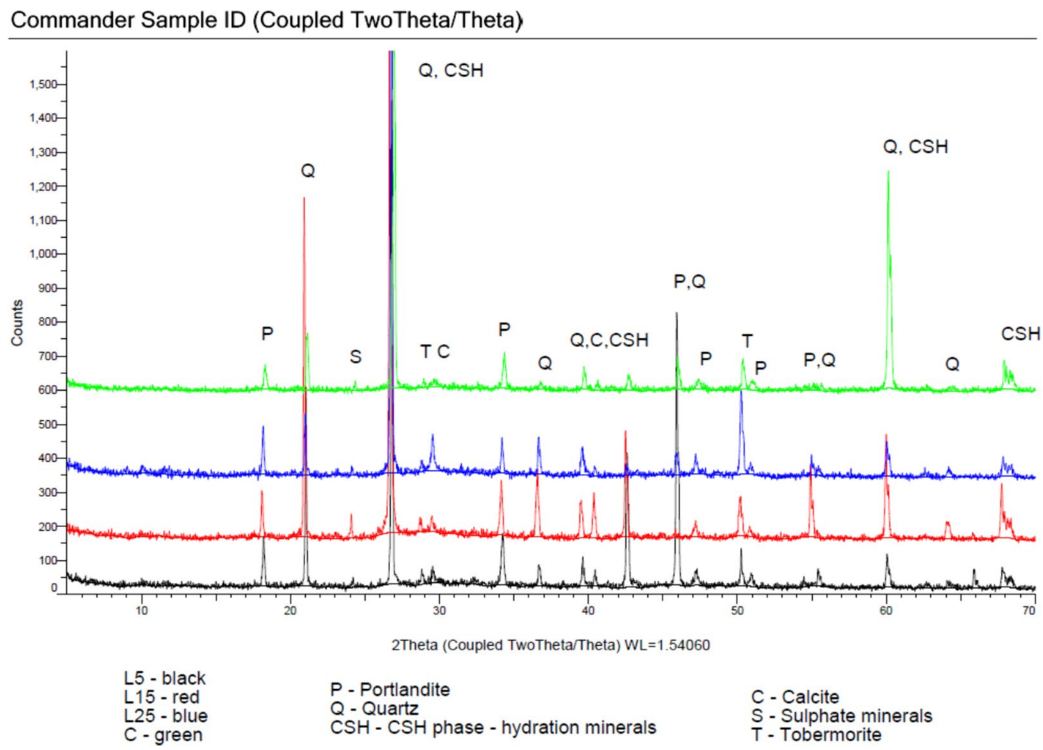

Fig. 20 XRD patterns of mortar samples containing RCP with different strengths of parent concrete

RCP-H. They were tested as components of a blended binder where they replaced 5%, 15%, and 25% of cement. Standard mortars were then prepared according to EN 196–1, to test selected properties and to investigate the role of the compressive strength of the parent concrete. The following can be concluded:

- The influence of the parent concrete strength on the flow of RCP fresh mortar was found to be insignificant;
- There is no clear observed effect of the strength of the parent concrete on the flexural and compressive strength of the next-generation cementitious mixture;
- The results also indicate that the grain size of the RCP has a greater effect on the final properties of the mortars than its compressive strength or the presence of CSH phases;
- Differences between the strengths of the L, M, and H mixtures are greater in younger ages (28 days), and they are levelling off with age. At 180 days, there is no significant difference between the strengths of these groups of samples;
- No significant effect of the strength of parent concrete was found also for water absorption and ultrasonic pulse velocity values of new-generation mortars;
- RCPs have shown a nice recycling potential to be incorporated in Portland fine-grain cements according to EN 196–6, reaching strength classes 32.5 and 42.5. Looking at the average results of all RCPs after 180 days, it can be noted that although the reductions in compressive strengths compared to the control value (69 MPa) are 30% (at 15% replacement) and 40% (at 25% replacement), the values at 48 MPa and 41 MPa, respectively, allow these replacements to be considered and further tested. The need for caution comes when considering a high-volume replacement of RCP (25%), especially in the case of low-strength parent concrete, as here a 28-day results are not as conclusive:
- Irrespective of the parent concrete's strength, strong linear relationships between ultrasound and compressive strength ($R^2_L = 0.876$, $R^2_M = 0.895$, $R^2_H = 0.882$), ultrasound and water absorption ($R^2_L = 0.795$, $R^2_M = 0.919$, $R^2_H = 0.767$), and compressive strength and water absorption ($R^2_{28} = 0.8502$, $R^2_{90} = 0.8272$, $R^2_{180} = 0.871$) were found using regression analysis. As expected, UPV increases with higher compressive strength and

lower water absorption in the mortar samples, and water absorption increases with lower compressive strength.

Although appropriate methods have been chosen in the experiment for the exact specification of the nature of the input materials used, their assumptions for efficacy in the new mixtures, as well as the resulting properties of the new mixtures, the study certainly has its limitations, arising from the fact that it is an initial basic research, reported for that reason as a case study (as mentioned in the introduction). It can be concluded that continued research would require, in particular, systematic and multiple analyses of input materials (RCP) as well as output materials (mortars, and these in a longitudinal time sequence) to understand the material dependencies so that a clear qualitative parameter could be determined to predict the effectiveness of RCP in new cementitious mixtures. The above would also need to be set up for the possibility of applying reproducibility principles. As yet, the compressive strength chosen by the authors, based on an interest in adding to the body of knowledge on this relatively new subject, as well as on practical expediency (ease of determination in the field, e.g., by a Schmidt hardness tester), does not appear to be sufficient for this purpose. It is preferable if it is supplemented by an additional parameter, e.g., chemical and mineralogical composition, content of hydration phases, rate and type of degradation, or if it is conditional on the achievement of certain processing parameters, e.g., granulometry, together with a determination of which of these parameters predominates in its influence on the final properties of the mixtures.

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Author contributions
AS: conceptualization, methodology, resources, supervision; validation, writing—original draft, writing—review and editing, and funding acquisition; JK: conceptualization, methodology, investigation, data curation, writing—original draft, and writing—review and editing; AE, MB, NJ, and PO: investigation; AU: methodology and validation.

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Data availability
Data are available on request from the authors.

Declarations

Ethics Approval and Consent to Participate
All authors of the manuscript confirm ethical approval and consent to participate following the Journal's policies.

Consent for Publication
All authors of the manuscript agree on the publication of this work in the International Journal of Concrete Structures and Materials.

Competing Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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