Use of recycled fines from waste concrete as an admixture in new concrete

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3.1 Introduction

The development of a circular economy is essential to build a better world. The UN's 17 Sustainable Development Goals is the most comprehensive plan for sustainable development. It includes the development of a circular economy as a manner of effectively scaling sustainable economic models within planetary boundaries. As the most used material worldwide, the recycling of concrete is a priority for this approach to reduce the consumption of nonrenewable resources.

The use of waste concrete to produce recycled aggregates is well-spread worldwide, gaining more and more space with the advance of knowledge and regulations. Under current regulations, coarse recycled concrete aggregates are permitted to produce structural concrete in many countries. The crushing process still produces a significant amount of fines, which are challenging to apply in structural concrete.

Fine recycled concrete aggregate (FRA) finds some inconveniencies for concrete production. It generally contains a significant amount of very fine and porous particles (Hincapié Henao & Aguja López, 2012; Sosa et al., 2012; Zega et al., 2010), mostly composed of loose mortar produced during the crushing process. As a consequence, the inclusion of FRA in concrete production commonly leads to a significant increase in water demand and other detrimental effects of properties in the hardened state (De Brito et al., 2005; Dhir et al., 1999; Hansen, 1986; Masood et al., 2001; Various, 2013; Zega & Di Maio, 2006, 2011). Moreover, the particle shape of FRA is inconvenient as it also increases paste demand in concrete to counteract the significant internal particle friction. A third concern is related to the contents of gypsum and other contaminants, which are more present in the fines than in the coarse fraction. Therefore new applications to valorize FRA in cementitious materials and prevent downcycling are desirable.

The Structural Integrity of Recycled Aggregate Concrete Produced with Fillers and Pozzolans.
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The utilization of the fines fraction produced during the crushing of waste concrete is still unresolved. This fraction represents up to 50% of the mass of waste concrete (Chen et al., 2019). It is a significant amount of waste that is generally considered a secondary leftover after the production of coarse recycled aggregate. Downcycling is very common for the whole fraction under 2 mm particle size. It is used for geotechnical purposes in unbound road substrates or landfills. Advanced beneficiation may increase the environmental impact reduction of recycling waste concrete. It is an important aspect of circularity of the concrete industry as the environmental impact of this leftover is generally attributed to the coarse fraction, diminishing its competitiveness with respect to virgin aggregates (Chen et al., 2019).

Consequently, there is interest in analyzing the possibility of FRA being used as an admixture in the production of new concrete. This kind of application may contribute to both the circularity in the concrete industry and reduction of the clinker factor in concrete (with a corresponding decrease in the carbon footprint). With some differences, applications as mineral admixture can valorize the very fines of the primary crushing or the fines produced by grinding all FRA under 2 mm size to make a recycled powder that can be used as an admixture.

3.2 Grinding, water demand, and potential filler effect

Recycled powder can be obtained from sieving FRA to separate the fine particles (e.g., below 75 μm) or complete grinding the FRA to produce a finer material. The second procedure involves additional energy consumption, but it can offer an all-inclusive solution for the FRA at the time it can improve some properties of the recycled powder. Sosa et al. (2015) found that ground FRA (GFRA) has lower cement paste content than sieved recycled powder, as hard particles from the natural aggregate are also reduced in size to become part of the recycled powder. This procedure results in a recycled powder with less overall porosity and more appropriate properties to be used as filler. Florea and Brouwers (2013) point out the convenience of a smart crushing process that can separate the different phases in waste concrete more efficiently by applying a variable crushing force to intermediate values between the strength of the aggregate and the one of the hardened paste. They were then able to obtain a recycled powder with higher contents of residual cement paste, which contributes to the more efficient valorization of the coarser fractions and poses challenges to the application of the recycled powder. However, this procedure may reduce the content of hard particles in the recycled powder, making the secondary grinding less energy demanding. Furthermore, thermal activation of recycled powder (see the section on it later) can be more efficient when the cement hydrates are concentrated in the fine fraction.

Therefore the primary crushing method has a considerable influence on the quality of the produced materials (Florea & Brouwers, 2013), including the recycled powder. An optimized crushing method can lead to better properties when the crushing force is selected according to the concrete strength. On the one hand, these manufacturing technologies will produce even more recycled powder as the cement paste is removed from coarse aggregates (Kim & Choi, 2012). On the other hand, it might be challenging to apply tailored procedures in the all-purpose recycling production chain. It seems more suitable for recycling some specific types of waste concrete which properties do not vary largely. Tailored crushing seems difficult to apply during the production of aggregate in recycling plants that receive quite variable types of waste concrete. It can therefore increase production costs and reduce the competitiveness of such recycled products. In these cases, the grinding of fines (e.g., 0–2 mm) might be a better option to obtain a steady quality of the recycled powder.

Moreover, the recycled powder obtained from sieving is typically coarser than GFRA. During secondary grinding, a target particle size distribution can be achieved to complement better the particle size distribution of cement. Sosa et al. (2015) showed that results regarding water demand and the compressive strength of mortar were better for GFRA in association with its finer particles with less content of cement paste than sieved recycled powder.

In principle, GFRA can work as an inert filler in cementitious mixes. Filler effect is produced when fine particles facilitate hydration through the provision of nucleation sites and additional space for the growth of cement hydration products on their surface, accelerating early hydration of cement and therefore the strength development (Arvaniti et al., 2015; Lawrence et al., 2003; Lohtia & Ramesh, 1995; Sosa et al., 2015). The reached fineness after a sensible grinding is critical in the study of the filler effect of GFRA on cement hydration (Lawrence et al., 2003).

A systematic investigation of the grinding process of FRA is presented by Laurente et al. (2016a). In that study, the FRA with size below 4.75 mm and the properties in Table 3.1 was obtained from 30 MPa concrete. That concrete was prepared with cement type I ASTM. The dry FRA was ground in a laboratory ball mill, with a ratio material/cylpebs of 10 kg/90 kg, progressively for 2:00, 2:45, and 3:30 hours, obtaining three different levels of fineness. The physical properties of the GFRA are shown in Table 3.2. The particle size is reduced with the progressive grinding, especially the maximum size (reflected in the d90 value), whereas the

Table 3.1 Physical and chemical properties of fine recycled concrete aggregate.

Physical properties		**Chemical properties**		
Density	2.60	CaO		8.97%
Water absorption	8.5%	IR		67.80%
Material <75 μm	2.5%	LOI	110°	0.94%
			550°	6.34%
			950°	10.10%

IR, Insoluble residue; *LOI*, Loss on ignition.
Source: From Laurente, R., Villagrán Zaccardi, Y. A., Zega, C. J., & Alderete, N. M. (2016a). Recycled powder as filler admixture in cementitious systems: Production and characterisation. In: Sixth Amazon & pacific green materials congress and sustainable construction materials Lat-RILEM conference, Cali, Colombia. UniValle.

Table 3.2 Variation in particle size with the grinding time.

Grinding period (h)	**Retained in sieve (%)**		**Density (g/cm^3)**	**Blaine specific surface area (cm^2/g)**	**Particle size distribution d10/d50/d90**
	45 μm	**75 μm**			
2:00	28.15/28.54	21.0/18.8	2.62/2.64	1093	1.3/15.6/70.1
2:45	27.00/26.00	15.4/14.2	2.63/2.65	1478	1.2/14.2/67.8
3:30	21.26/20.75	10.2/10.4	2.63/2.63	1975	1.1/12.2/55.3

Source: From Laurente, R., Villagrán Zaccardi, Y. A., Zega, C. J., & Alderete, N. M. (2016a). Recycled powder as filler admixture in cementitious systems: Production and characterisation. In: *Proceedings of the Sixth Amazon & Pacific green materials congress and sustainable construction materials Lat-RILEM conference*, Cali, Colombia. UniValle.

changes are less significant for the distribution of lower fractions (d50 and d10). This means that the increased grinding period is mostly useful for reducing the size of coarse particles, which are expected to be composed of natural rock and the hardest ones at the same time. Then, little improvement is obtained with extended grinding as the impact is almost only seen in a small relative volume of the GFRA and limited enhancement of the potential filler effect. Such results are consistent with those reviewed by Tang et al. (2020), who found optimal periods between 60 and 180 minutes reported in the literature. Heterogeneity among constituting phases is an important aspect determining the effectiveness of grinding, so such optimal periods seem to be much related to the constituents of the parent concrete.

Extended grinding of FRA can increase its fineness and external specific surface area, but it also changes the porous properties of the material. Li et al. (2020) measured both the BET external and micropore specific surface areas of recycled powders with variable fineness degrees (Fig. 3.1). As the grinding reduces the particle size, the pore walls are exposed, and the porosity of particles is also decreased. Therefore the grinding process can change the mechanisms by which the recycled powder affects the fresh properties of mixes.

In general terms, significant changes in the particle size distribution of cementitious materials have a noteworthy impact on the water demand (and hence on concrete workability). A higher fineness level of the binder increases the amount of water required to achieve the target consistency. Improved particle size distribution could contribute to optimizing the particle packing and reducing the water demand of the blend of cementitious materials. Oksri-Nelfia et al. (2016) showed improved packing densities with cement replacement by recycled powder ($d50 = 8.8$ μm). They connected this improved packing with the reduced water demand they measured, because of a lower filling requirement of voids between particles. In this

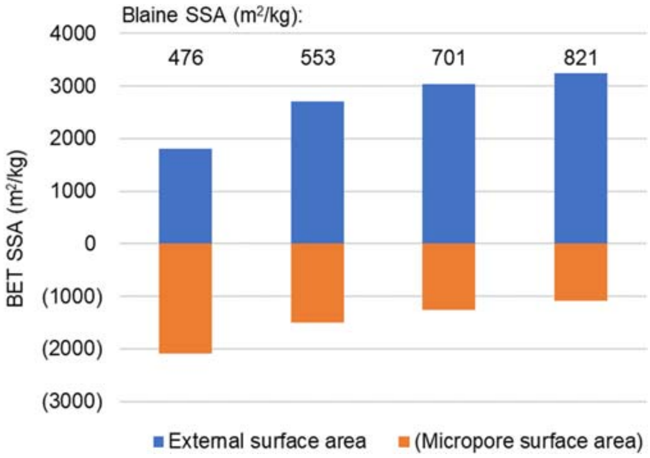

Figure 3.1 External and internal BET SSA of recycled powders with a variable fineness level.
Source: Modified from Li, S., Gao, J., Li, Q., & Zhao, X. (2020). Investigation of using recycled powder from the preparation of recycled aggregate as a supplementary cementitious material. Construction and Building Materials. 267, 120976.

regard, Bordy et al. (2017) found that the slump of mortar prepared with different proportions (10%–100%) of ground cement paste (GCP) (d50 = 12 μm) as a replacement for Portland cement was similar to that of mortars prepared with 100% Portland cement despite the replacement proportion. The authors explain this finding as a consequence of a similar particle size distribution of GCP and the cement it replaces. Thus inert particles finer than those from cement improve the performance regarding bleeding, setting time, heat evolution, strength, and durability (Swamy, 1998). However, GFRA has its high porosity as an additional aspect to be considered. Li et al. (2020) showed that the reduction in mortar flowability can be connected to the fineness of the recycled powder. In this case, a larger specific surface area increases water demand. Then, fresh mortar with the incorporation of finer recycled powder is expected to have lower flowability and greater slump loss (Fig. 3.2). Tang et al. (2020) reported an increase in water demand between 5% and 20% depending on the GFRA content and type. Such effects may be associated with the presence of cement paste in the recycled powder, as recycled powder obtained from brick waste did not show affectation of the flowability of similar mixes. The changes in fineness in Laurente et al. (2016a) affected the water demand of pastes prepared with 15% and 30% replacement ratio of cement. However, the water affinity of the porous GFRA is relatively compensated by the dilution effect on cement resulting in similar water demand. In fact, Ma and Wang (2013) reported a reduction in water demand with the increasing replacement ratio of cement by recycled powder. The cement used in that study has a quite high water demand (30%), which can explain the diluting effect of the recycled powder. It is likely that

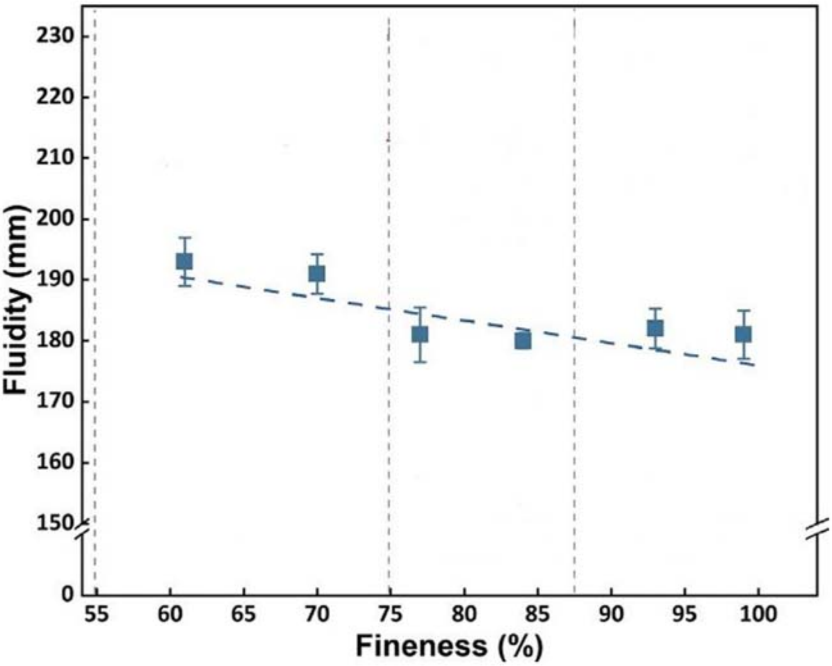

Figure 3.2 Fluidity of mortar with 30% wt. cement of recycled powder with different fineness levels (100% corresponds to Blaine SSA = 821 m^2/kg).
Source: Modified from Li, S., Gao, J., Li, Q., & Zhao, X. (2020). Investigation of using recycled powder from the preparation of recycled aggregate as a supplementary cementitious material. *Construction and Building Materials*. 267, 120976.

if less fine cement had been used, the effect of the recycled powder would have been much less (and probably imperceptible). Sosa et al. (2015) showed that the effect on water demand is related to the amount of attached cement paste in the recycled powder. This content can vary significantly depending on how this recycled powder is produced (i.e., when obtained by grinding as for GFRA a lower porosity and content of cement paste is obtained than when obtained by sieving of FRA). Therefore a more significant water demand could be expected if the recycled powder is obtained from sieving FRA resulting from primary crushing. Also, Cantero et al. (2020) reported increased water demand that they explain by the internal porosity of recycled powder particles that are coarser than cement particles.

Regarding the compressive strength, there was a notorious dilution effect of the cement when replacing 15% and 30% of its content by GFRA in mortars (Laurente et al., 2016a). However, the cement efficiency (the compressive strength divided by the unitary cement content) showed no decreased values with the replacement ratio (Fig. 3.3). Similar cement efficiencies were found by Cantero et al. (2020) when replacing 10% and 25% of cement with recycled powder in concrete. Furthermore, from the comparison of cement efficiencies of mixes with 15% replacement and the

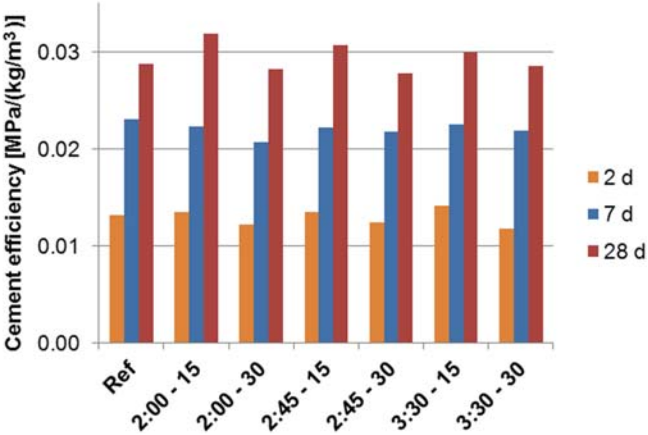

Figure 3.3 Cement efficiency regarding compressive strength in GFRA blended mortars. *GFRA*, Ground FRA.
Source: From Laurente, R., Villagrán Zaccardi, Y. A., Zega, C. J., & Alderete, N. M. (2016a). Recycled powder as filler admixture in cementitious systems: Production and characterisation. In: *Proceedings of the sixth Amazon & Pacific green materials congress and sustainable construction materials Lat-RILEM conferenc*e, Cali, Colombia. UniValle.

control mix in Laurente et al. (2016a), a slight filler effect is possible for all degrees of fineness of GFRA. When analyzing several fineness degrees, Li et al. (2020) found a small increase in the strength activity index of mortar containing finer recycled powders. The contribution was more notorious at 28 days than at 90 days, suggesting that it might be due to a physical effect on cement hydration rather than by the reactivity of the recycled powders themselves.

The similar or slightly better cement efficiency leads to environmental benefits of the partial replacement of cement by recycled powder. Pavlů et al. (2016) and Cantero et al. (2020) presented results from the life cycle assessment of concrete that are advantageous regarding the use of recycled powder. Especially the global warming potential is conveniently reduced, directly connected with the lower cement consumption. In this sense, electric power consumption for grinding seems to be the main contributor to the global warming potential of the recycled powder, with an estimated value between 0.188 kg CO_2eq/kg (Cantero et al., 2020) and 0.245 kg CO_2eq/kg (Tan et al., 2020). Therefore the optimization of grinding is critical for the ecoefficiency of the recycled powder, and extended grinding times seem unadvisable.

Regarding hydration at very early ages, setting times were slightly affected by the fineness of GFRA in Laurente et al. (2016a) (Fig. 3.4). The penetration resistance of blended pastes was higher than the control paste for 2 hours of grinding time of GFRA and lower for grinding times of 2:45 and 3:30 hours. Thus for 2 hours of grinding the main effect seems to be dilution, with a delay in the development of penetration resistance with time. For more extended grinding periods, this effect is offset, presumably, by the enhancement of hydration through the provision of additional nucleation sites by the fine GFRA. Then, the filler effect causes

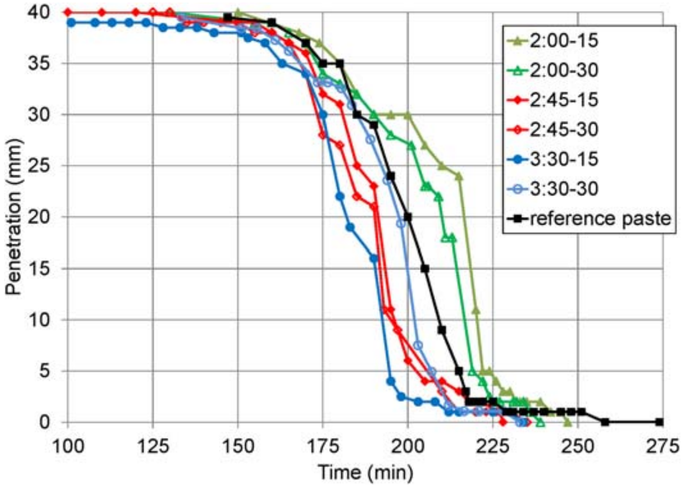

Figure 3.4 Setting times for variable fineness degree of GFRA. *GFRA*, Ground FRA. *Source*: From Laurente, R., Villagrán Zaccardi, Y. A., Zega, C. J., & Alderete, N. M. (2016a). Recycled powder as filler admixture in cementitious systems: Production and characterisation. In: *Proceedings of the sixth Amazon & Pacific green materials congress and sustainable construction materials Lat-RILEM conference*, Cali, Colombia. UniValle.

the earlier development of penetration resistance for 2:45 and 3:30 hours. In any case, the net effect is small, and whereas this is observed for the evolution of the penetration resistance, it is not very clear from the standard setting times.

Oksri-Nelfia et al. (2016) also verified earlier heat release with increasing contents of recycled powder (d50 = 8.8 μm). These effects were slightly lower than those of equivalent contents of limestone powder with almost the same particle size. The additional space provided by the recycled powder also contributes by increasing the hydration degree of cement. The appropriate complement of the cement particle distribution by a fine recycled powder shows advantages at early ages. Still, it seems insufficient to compensate for the dilution effect on later strengths when replacement ratios are over 20%.

Results show that applications as filler for obtaining well-graduated systems may be a good option for GFRA. This alternative would allow lower energy consumption for grinding of FRA to a not very high fineness and potentially be used in the production of self-compacting concrete (SCC). The substitution of virgin limestone filler and simultaneous valorization of FRA as secondary material seems a good contribution to circularity in the concrete industry.

3.3 Hydraulic activity in recycled concrete fines

Some researchers have suggested that anhydrous cement grains in FRA under 2 mm size may further develop hydraulic activity when properly processed (Katz, 2003;

Khatib, 2005; Khoshkenari et al., 2014; Oksri-Nelfia et al., 2016; Poon et al., 2006). Such hydraulic activity has been supported by weak cementation of loose FRA stored outdoors and exposed to moisture (Arm, 2001; Zega et al., 2017), and by small amounts of heat release (15 J/g) during isothermal calorimetry of pure recycled powder mixed with water (Oksri-Nelfia et al., 2016). Martinez-Echevarria et al. (2020) studied the Californian Bearing Ratio (CBR) of FRCA samples obtained by sieving, grinding, and a 50% combination of both. They found that CBR values increased with immersion and additional grinding cycles, suggesting the presence of cementing activity.

The potential amount of anhydrous phases in the hardened cement paste depends on the w/c ratio of the parent concrete. It is more likely that anhydrous cement is present in mixes with a low w/c ratio. The presence of fly ash and other supplementary cementitious materials could also contribute to the additional reactivity of the concrete powders. In fact, if the recycled powder contains a certain amount of clay waste, portlandite consumption has been reported, indicating possible pozzolanic activity (Zhu et al., 2019). However, the effective benefits of the reactivity of recycled powder on the properties of blended mixes have not been thoroughly studied yet, and its extent may be too little to be noticed in concrete mixes.

Bordy et al. (2017) studied the properties of GCP made in the laboratory (90 of curing under water, $w/c = 0.30$, $d50 = 12\ \mu m$) and its influence on mortars. Replacement levels of Portland cement by GCP between 10% and 100% were analyzed. The theoretical computations based on TGA of the GCP suggested a limited degree of hydration and the potential presence of 24% of anhydrous cement. However, this high content of anhydrous cement could not be confirmed by Fourier transform infrared spectroscopy. The TGA results were in agreement with those of hydration kinetics (semiadiabatic calorimetry) and compressive strength of the studied mortars. For hydration kinetics, the temperature peak increased with the presence of hydraulic activity. In the same sense, although the compressive strength decreased with cement content, some microstructure development was observed for 100% GCP. The compressive strength of 100% GCP mortar was 7.92 MPa after 90 days of curing. It is clear that the presence of anhydrous cement in recycled aggregates is very likely. However, FRA is expected to have only a fraction of the contribution reported for GCP in connection with the dilution effect by natural aggregate phases. Unless beneficiation actions are implemented, a negligible contribution from anhydrous cement in FRA is expected.

Amin et al. (2016) studied the cementing contribution of FRA by calorimetric measurements, SEM observations, and compressive strength. They prepared mortars with variable replacement ratios of cement by FRA (0–4 mm). From a special calorimetric measurement, the authors report a heat release occurring immediately after wetting that was higher for FRA than for anhydrous cement. They claim that this is caused by the presence of chemically active aluminous compounds, but this is not entirely clear. From SEM observations, the authors reported gel formation on the surface of FRA particles, which they attributed to reactive phases on the surface of particles. The effect of FRA on the compressive strength of mortars was negative, with decreasing values as the percentage of replacement (10, 20, 25, 50, 60, and 75% wt.) of cement by recycled fines increased. However, when fine sand was used instead of FRA, even lower compressive strength was obtained. Therefore some contribution of FRA to strength development is presumed. Other potential causes for the influence on strength would be the unintentional modification of the effective w/c ratio due to water uptake of FRA in the fresh mix or the contribution made by the roughness of FRA particles. However, the authors also reported higher compressive strength in mortars made with freshly produced FRA, in comparison with FRA that was used after 90 days of storage under water. The differences can be attributed to some cementing contributions of the former.

The presence of anhydrous cement in FRA was also reported by Prošek et al. (2020) from calorimetric measurements and compressive strength of mortars made with GFRA as cement replacement. Again, decreases in compressive strength were found, but these were of little significance up to GFRA contents of 30% wt. In contrast, the authors report increases in tensile strength of up to 200% as a consequence of the bridging of microcracks by inert inclusions contained in GFRA.

Sosa et al. (2015) investigated the cementing properties of both the fines contained in FRA and GFRA. Recycled powder with size under 75 μm (P75) obtained from sieving FRA and recycled powder produced from the grinding of FRA (P600) were analyzed. Particle size distribution showed a higher fineness for FR600 (d10/d50/d90 = 0.4/9.7/53.9 μm) than for FR75 (d10/d50/d90 = 0.6/32.2/72.0 μm). A significant potential difference between each powder is that when processing FRA by grinding it, anhydrous cement particles in the attached mortar are exposed, which can mean a potential contribution to the cementing capability of the powder. Besides, P75 had probably a higher cement paste content than P600, and the fines produced during the first crushing process come from the weakest phase in the waste concrete (i.e., weak cement paste). The situation is different for P600, as when FRA is completely ground to produce P600, the resulting material is composed of a larger amount of natural aggregate. P75 would then be presumably more porous and less reactive than P600; this is clearly supported by the reported differences in density (2.70 for P600 vs 2.60 for P75). No peaks associated with belite or alite were noted in XRD patterns either in primary (P75) or processed (P600) recycled powder (Sosa et al., 2015), showing that any content of these phases is surely below the detection limit (0.5%). Thus no content of anhydrous cement could be confirmed. The lack of reactivity can be related to insufficient fineness in the recycled powder that incompletely exposed the anhydrous cement grains in the recycled powder. However, Li et al. (2020) also investigated the strength activity index, and they found more contribution to initial strength development, whereas no activity was obtained later at 90 days. Consequently, cementing activity from the recycled powder may contribute to some improvement in the ITZ that these particles form with the new cement paste. However, the relative contribution of anhydrous phases to the mix is minimal, and it seems hard to detect by analyzing the properties of the resulting mortar.

Then, the potential contribution of recycled powder to the development of microstructure was assessed by the strength activity index in mortars. Sosa et al. (2015) prepared mortars replacing 35% of cement with recycled powders P75 and P600. They obtained strength drops of 35% or higher, showing a lack of compliance with

ASTM C 618-03 due to a clear dilution effect. Therefore the recycled powder did not contribute to strength gain. Similar results were reported in Kang and Li (2019), Oliveira et al. (2020), and Pavlů et al. (2016), where the dilution effect of sieved recycled powder (particle size below 125, 160, and 150 μm, respectively) was predominant. Slightly better results for the strength activity index (80%) were reported by Duan et al. (2020) when substituting 30% of cement by a GFRA finer (d10/d50/d90 = 1/9/30) than P600 in Sosa et al. (2015). It seems that increasing the fineness of the recycled powder can be effective in reducing its dilution effect. In any case, the cement efficiency (compressive strength relative to cement content) remains almost the same showing no detrimental effect in the mix and potential applications for SCC where the recycled powder can play a role as inert filler.

An extensive statistical analysis of data in the literature on the influence of GRCA on compressive strength is presented in Tang et al. (2020) (Fig. 3.5). The dilution effect is clear, with an obvious detrimental impact when GFRA replaces more than 30% of cement. Some contribution to strength development was also observed with extended grinding to obtain particle size below 75 μm, compared to shorter grinding to obtain particle size only below 150 μm. It is unclear how much of this improvement can be related to reaction of the GFRA itself and how much can be related to an improved filler effect. However, the gain is not significant. In addition, the composition of the parent concrete appears to be among the variables that have the greatest influence on the potential cementing contribution or filler effect of GFRA. It seems necessary to substantiate the convenience of extended grinding by analyzing the ecoefficiency of the additional energy consumption in relation to the small gain in compressive strength.

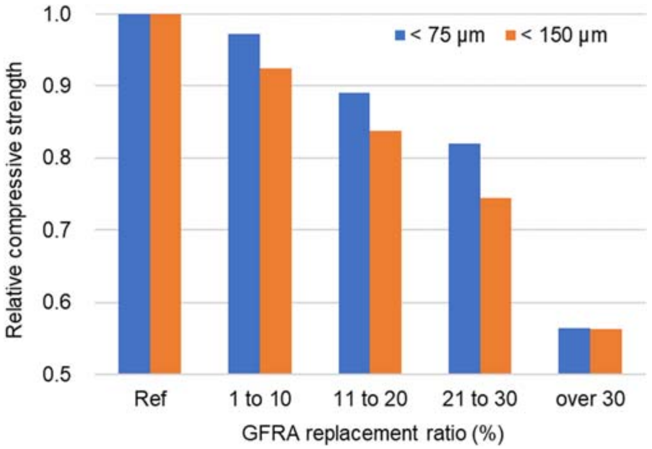

Figure 3.5 Relative strength as a function of the GFRA replacement ratio and fineness. *GFRA*, Ground FRA.
Source: Modified from Tang, Q., Ma, Z., Wu, H., & Wang, W. (2020). The utilization of eco-friendly recycled powder from concrete and brick waste in new concrete: A critical review. *Cement and Concrete Composites*, 114, 103807.

3.4 Thermal activation

Hydrated cement paste decomposes progressively with temperature (Alonso & Fernandez, 2004). Temperatures of up to 105°C mainly lead to the evaporation of free water in the pore structure. Some phases, such ettringite, also start decomposing at that temperature. At temperatures higher than 105°C, the dehydration of cement hydrates proceeds after free water has been completely desorbed. Above 450°C, portlandite decomposes, and the content of CaO increases. Above 650°C more CaO is produced due to decarburization of carbonates. Around 800°C, C-S-H is almost entirely dehydrated.

Serpell and Lopez (2013) found that the dehydration temperature affects the reactivity of thermally activated cement paste. They report that increasing the temperature up to 800°C may decrease the early strength (7 days) of mixes prepared with it, but it improves the later strength (28 and 90 days). Increasing the fineness of the recycled powder can compensate this effect, and with fine recycled powder calcined at 800°C, convenient strength development can be obtained at both early and later ages. Another critical aspect detected by Serpell and Lopez (2013) was the dilution ratio of cement hydrates in the cementitious material under thermal treatment. In this regard, if insufficient cement hydrates were present in GFRA, the cost-effectiveness of a thermal treatment will be hindered. Thus it seems that the manufacturing procedure should adequately address this issue in search of energy-efficient treatments.

Furthermore, Shui et al. (2008) determined that the structure of rehydrated products in recycled powder treated at 500°C is looser than that of ordinary cement paste. Then, for the same content of anhydrous material, a lower contribution to the development of microstructure is expected for recycled powder compared with cement. Convenient complementation of cement particle size distribution is still quite advantageous, meaning that even a reduced contribution of active recycled powder can be justified when coupled with appropriate particle size distribution.

When thermally reactivated cement pastes were used as mineral admixtures for the production of mortar, Serpell and Lopez (2015) found that calcination at 800°C leads to significant production of free lime. Fig. 3.6 exemplifies such an increase with increasing calcination temperatures. Increases in the free lime content are noted above 400°C (with the dehydroxylation of calcium hydroxide) and even more significantly at 700°C (with the decomposition of calcium carbonate). This compound affects early hydration by releasing significant amounts of heat (and potentially produces a false setting). The risk of this effect can be reduced in ternary systems that incorporate also fly ash or other supplementary cementitious material. Supplementary cementitious material dilutes the content of free lime and consumes later the portlandite formed by the fast hydration of it (Serpell & Lopez, 2015; Shui et al., 2008). The problem with free lime in this study is serious as pure cement paste was used as source material for producing the thermally activated recycled powder. In recycled powder coming from waste concrete, the cement hydrates (and particularly portlandite and calcite) are much diluted, and the risk of fast hydration of phases is reduced.

The application of reactivation temperatures above 800°C is objected by Serpell and Lopez (2015). The dehydration of C-S-H produces increasing amounts of alpha-C_2S up to a maximum at that critical temperature, above which it starts decreasing as it reverts to beta-C_2S on cooling (with a lower contribution to strength development during rehydration). Moreover, XRD analysis showed that larnite and calcium silicates (Ca_3SiO_5 and β-C_2S) are formed with calcination temperatures of 800°C (Sui et al., 2020; Tang et al., 2020). These anhydrous silicates will react with water when the treated GFRA is added as a mineral admixture. However, the microstructure development is different from the hydrates formed with the hydration of clinker, and these aspects deserve more attention.

Shui et al. (2009) also reported an effect of dehydration temperature on the mechanical performance of mortar made with the dehydrated cement paste. This was attributed to a rough and scraggly microstructure. Also, a higher water demand was reported for higher dehydration temperatures. In another approach, Shui et al. (2011) concluded that it is possible to use the dehydrated cement paste to activate fly ash. By optimizing the Ca/Si balance of the blend, an extensive reaction of fly ash with dehydrated cement paste was achieved. This offers also a potential contribution to alkali-activated materials.

To study the feasibility of increasing the reactivity of GFRA by thermal activation, Carrizo et al. (2018) used calcined GFRA as a partial substitute for Portland cement. Two calcination temperatures were considered, 550°C and 800°C. At replacement ratios of 15% and 30%, effects on setting times and compressive strength were evaluated. The source concrete to produce the GFRA was a 30 MPa OPC concrete, which was crushed and sieved through a 4.75 mm opening mesh.

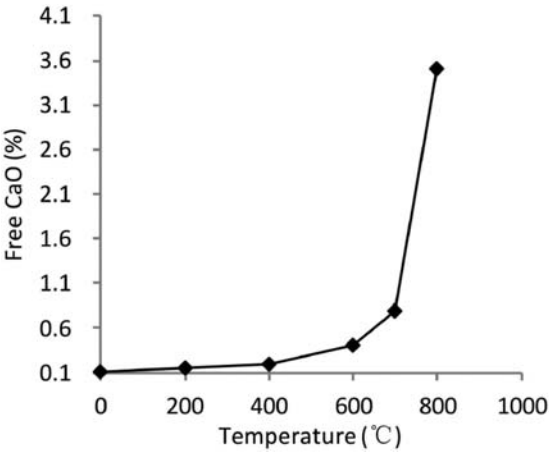

Figure 3.6 Free-CaO in treated GFRA depending on the calcination temperature. *GFRA*, Ground FRA.
Source: From Sui, Y., Ou, C., Liu, S., Zhang, J., & Tian, Q. (2020). Study on properties of waste concrete powder by thermal treatment and application in mortar. *Applied Sciences (Switzerland)*, 10(3), 998.

Then, the dry passing material (porosity = 20.3%) was ground for 2 hours in a ball mill with a material/cylpebs ratio of 10 kg/90 kg. Three series of the recycled powder were analyzed, a control material without any thermal treatment (PSC), one calcined at 550°C for 1.5 hours (PC5), and one calcined at 800°C for 2 hours (PC8). The calcination times were chosen to secure a full transformation of phases. Fig. 3.7 shows the particle size distribution of each recycled powder. The thermal treatment caused a small decrease in the highest peak of the curve, which could relate to the increase in dry density from 2.40 (PSC) to 2.41 (PC5) and 2.53 (PC8). Similar results were reported in Sui et al. (2020), who explained it as an effect of the structural transformation of C-S-H, and the consequences changes in the specific surface area and the pore volume of cement paste.

Table 3.3 shows the effect of the calcined GFRA on water demand obtained in Carrizo et al. (2018). No significant differences were noted for 15% replacement ratio. However, the replacement of cement by 30% of calcined GFRA increased water demand significantly, especially for GFRA calcined at 800°C. Such an increase may be attributed to augmented reactivity of the powder.

When the effect on setting was analyzed, results were not conclusive (probably due to the differences in water demand). Fig. 3.8 and Table 3.4 show setting curves and setting times, respectively, for the blended pastes studied in Carrizo et al. (2018). A significant delay in setting was observed for 15% replacement with the two types of calcined powder, but this effect seems to decrease for 30%

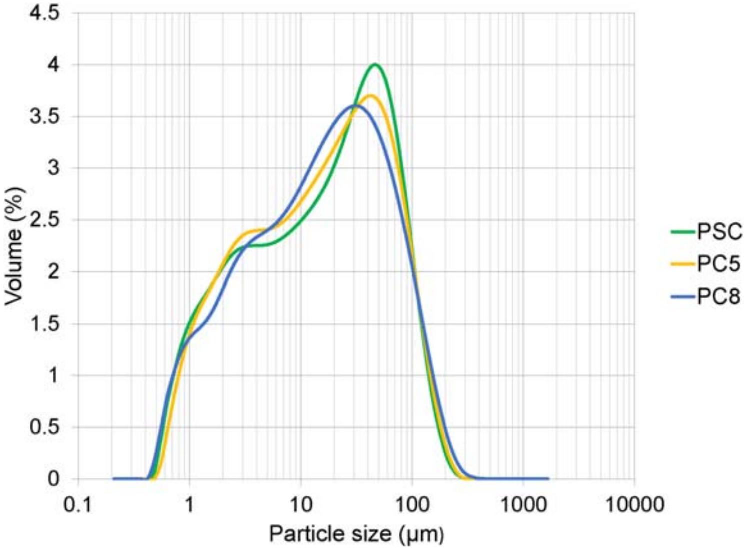

Figure 3.7 Particle size distribution of (un)calcined GFRA. *GFRA*, Ground FRA. *Source*: From Carrizo, L. E., Villagrán Zaccardi, Y. A., Alderete, N. M., & Zega, C. J. (2018). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VIII Congreso Internacional de la AATH* (pp. 63–69). AATH.

Table 3.3 Water demand of pastes with 15% and 30% of recycled powder contents.

ID	% of replacement	Water demand (%)
Ref.	0	27.0
PSC	15/30	26.7/26.7
PC5	15/30	27.3/28.4
PC8	15/30	27.2/30.4

Source: From Carrizo, L. E., Villagrán Zaccardi, Y. A., Alderete, N. M., & Zega, C. J. (2018). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VIII Congreso Internacional de la AATH* (pp. 63−69). AATH.

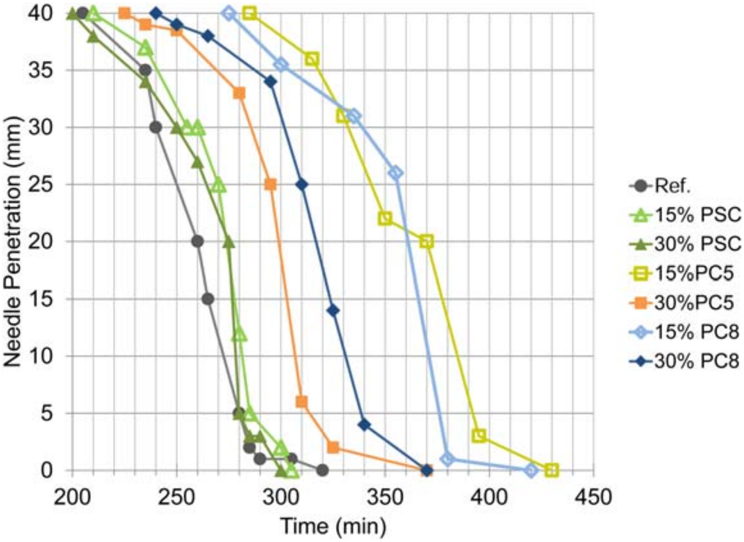

Figure 3.8 Setting assessment (Vicat method).
Source: From Carrizo, L. E., Villagrán Zaccardi, Y. A., Alderete, N. M., & Zega, C. J. (2018). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VIII Congreso Internacional de la AATH* (pp. 63−69). AATH.

replacement. These results are inconclusive, but it is possible to explain them by the combined actions of increased water demand, dilution effect of hydraulic phases in the pastes, and filler effect of the GFRA. From the combination of the three actions, it seems that 15% replacement ratio is the most convenient.

The optimal replacement ratio of 15% was confirmed by the compressive strength (standard mortars with water/binder of 0.50 and sand/binder of 3). Fig. 3.9 shows the values of the compressive strengths, and Fig. 3.10 shows the values of cement efficiency. In general terms, the compressive strength decreases with increasing replacement ratio for untreated recycled powder showing the prevalent dilution effect. Consequently, the reduction in strength at 2 days is proportional to

Table 3.4 Setting times for pastes blended with calcined ground fine recycled concrete aggregate.

	Initial setting (min)	Final setting
Ref.	230	320
15% PC5	315	440
15% PC8	298	418
15% PSC	235	305
30% PC5	240	350
30% PC8	294	370
30% PSC	220	300

Source: From Carrizo, L. E., Villagrán Zaccardi, Y. A., Alderete, N. M., & Zega, C. J. (2018). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In *Memorias VIII Congreso Internacional de la AATH* (pp. 63–69). AATH.

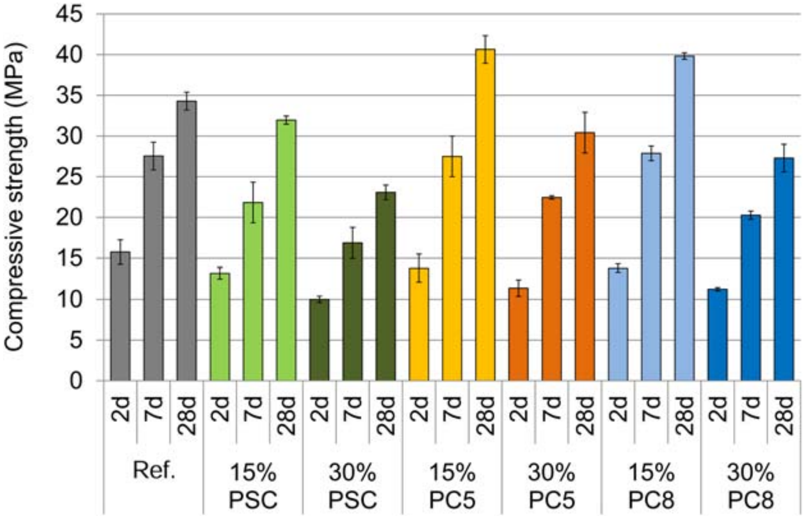

Figure 3.9 Compressive strength in blended mortars.
Source: From Carrizo, L. E., Villagrán Zaccardi, Y. A., Alderete, N. M., & Zega, C. J. (2018). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VIII Congreso Internacional de la AATH* (pp. 63–69). AATH.

the replacement ratio for all the types of recycled powder. However, for the thermally treated recycled powder, the reduction in strength at 7 days is lower than that corresponding to a plain dilutive effect. Moreover, at 28 days mortars containing 15% of PC5 and PC8 showed higher strengths than the reference mortar. There is a meaningful contribution of the thermally treated recycled powders at later ages. This contribution is highlighted when the cement efficiency (MPa per kg/m^3 of cement) is computed. Significant improvements on cement efficiency at 7 and 28 days are noted with the use of PC5 and PC8, again with 15% replacement ratio as the best option in this regard.

Previous results are more conservative than those presented by other researchers. Sui et al. (2020) suggest replacement ratios of up to 30% if the GFRA is pretreated at 700°C, whereas Kalinowska-Wichrowska et al. (2020) suggest replacement ratios of up to 25% if GFRA is pretreated at 650°C. In the first study, the inclusion of 30% calcined GFRA produced a reduction in strength of between 15% and 20%. In the second study, the inclusion of 25% calcined GFRA produced even an increase in strength of 7% in comparison with the control mortar. However, those studies do not report results for lower replacement ratios, meaning that results are not contradictory with the previous. Better performance might have been obtained with replacement ratios of around 15%.

He et al. (2019) compared the CO_2 emissions of recycled cement produced by thermal treatment (at 450°C and 800°C) of GCP with those of standard Portland cement. The specific chemical emissions for recycled cement were 0.048 and 0.19 tons of CO_2 per ton of cement, for calcination temperatures of 450°C and 800°C, respectively. The properties of the pastes prepared with both cements were investigated for their hydration kinetics, compressive strength, and CO_2 capture capacity. Contrary to the results obtained by other researchers, the compressive strength of cement paste prepared with recycled cement treated at 450°C was similar to that of the control paste made with 100% Portland cement. The compressive

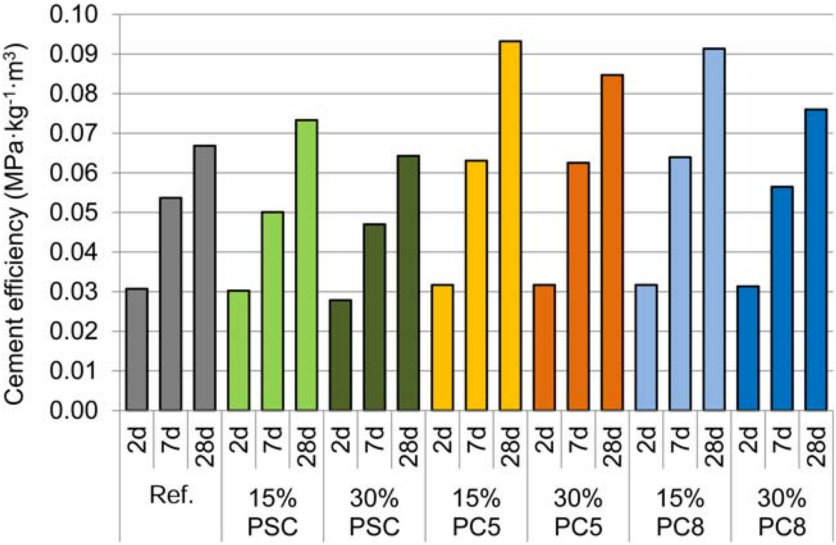

Figure 3.10 Cement efficiency regarding compressive strength.
Source: From Carrizo, L. E., Villagrán Zaccardi, Y. A., Alderete, N. M., & Zega, C. J. (2018). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VIII Congreso Internacional de la AATH* (pp. 63–69). AATH.

strength of recycled cement produced at 800°C was lower, representing only 68% of the compressive strength of the reference cement paste. The authors do not fully explain the reason for the very auspicious results for the recycled cement produced at 450°C. Differences in mineralogical composition were reported, and as expected the main phases of Portland cement were C_2S and C_3S, while for 450°C recycled cement the main phases were calcite, 1.4 nm tobermorite, and jennite, and for 800°C recycled cement they were lime, wollastonite, and C_2S in a small amount. Rehydration of tobermorite and jennite may contribute to microstructure development, but it is questionable whether this rehydration is comparable to microstructure formation from C_2S and C_3S. Further studies are required to confirm this hypothesis.

Thermal activation of recycled powder to use as a supplementary cementitious material may represent a significant contribution to reducing the carbon footprint of cement production. However, the results differ depending on the concentration of cement paste in the recycled powder. Auspicious results have been reported for GCP, while the use of GFRA with a lower content of hydration products seems less beneficial. It seems opportune to investigate a possible combination of this valorization for the recycled fines with an advanced processing for extended liberation of particles for the coarse fractions. Such an approach would improve the properties of the coarse recycled aggregate while concentrating the hydration products in the fines fraction. In addition, a life cycle assessment of the production and use of recycled powder as supplementary cementitious material is required to confirm the reduced environmental impact. Despite some limited impact, thermal activation has the advantage of being less energy-intensive than other valorization alternatives.

A more advanced application of GFRA than its use as supplementary cementitious material is in the production of clinker. GFRA can be used as an alternative raw meal to partially replace virgin limestone and clay (Schoon et al., 2015). Such application is out of the scope of the present review, but it is also interesting for the production of low carbon binders (De Schepper et al., 2014; Snellings et al., 2012). The decomposition of calcium carbonate from limestone (releasing significant amounts of CO_2) is partially avoided with alternative sources of calcium such as portlandite and C-S-H, which require lower temperatures than calcium carbonate to provide the necessary lime. Moreover, chemical emission savings are achieved as lime is produced by releasing combined water instead of CO_2. It seems convenient that GFRA is uncarbonated, since the content of calcite will increase chemical emissions and portlandite decomposes at a lower temperature than calcite. Still, the CaO content in GFRA increases when it comes from limestone aggregate concrete. Then, a higher proportion of GFRA in the raw meal can be used with reductions in indicators for environmental impact different from global warming potential.

3.5 Use as fines in self-compacting concrete

A straightforward application of GFRA as filler would be its use in SCC. SCCs must comply with filling capacity, flow capacity, and resistance to segregation. In principle, the addition of GFRA could contribute to the cohesiveness of the mix by increasing the content of fines in concrete. These fines are responsible for maintaining the cohesion of the mixture, avoiding segregation, and carrying the coarser particles when the concrete is flowing. As this application means a complement to the granular skeleton, it does not require a very small particle size. SCC might then be an alternative for the valorization of GFRA and a contribution to reduced consumption of limestone filler usually used in its production.

Sun et al. (2020) produced and tested SCC containing low contents of GFRA (34 and 68 kg/m^3). They used the recycled powder in partial and full replacement of fly ash as filling admixture. Negative impacts on the slump flow, T_{50}, and V-funnel time were reported with the increase in the GFRA content. The effect is mostly attributed to the absorbing capacity of the recycled powder that causes a decline in the fluid performance of self-compacting mixes. For relatively coarse GFRA (D50 of 90 and 176 μm) Kim and Choi (2012) reported a decrease in viscosity and yield stress of pastes (without superplasticizer) as the content of recycled powder increased. This explains the effect by the dilution of cement caused by the GFRA. The impact of GFRA can undoubtedly raise the risk of segregation in fluid mixes, and it is quite an inconvenience in the design of self-compacting mixes. Potentially, a combined solution involving additional water and viscosity modifier might compensate for the detrimental effect of GFRA on the flow of SCC resulting from the combination of water absorption and dilution of cement. However, such a solution might increase the costs and reduce the competitiveness of GFRA as a filler.

The effect on fresh properties also translated into the compressive strength of hardened SCC (Sun et al., 2020). In this case, the recycled powder was used in replacement of a more active supplementary cementitious material such as fly ash. Such a dilution effect on the compressive strength is thus to be expected. The effect of the GFRA was more notorious after 28 days of curing than after 7 days of curing, precisely due to the lost contribution of the fly ash to the strength development.

However, the dilution effect can have a positive side, as pointed out in Kim (2017) when reporting reduced shrinkage with the incorporation of recycled powder. The high binder content in SCC can pose some issues regarding drying shrinkage, so the potential contribution of recycled powder in this regard deserves special attention. Preliminary results show that when the recycled powder is compared with other mineral admixtures such as ground slag or limestone powder, its effect on drying shrinkage of SCC is less favorable (Quan & Kasami, 2018). The effect of recycled powder on long-term properties of SCC is an aspect that deserves additional research.

From microstructural analyses, it was observed that the fine GFRA particles produced a filler effect and contributed to cement hydration by the provision of nucleation sites for portlandite (Sun et al., 2020). Such an effect is comparable to that of any other admixture. However, special attention should be paid to the water affinity of the recycled powder, as when this is especially fine, some particle agglomeration can adversely affect cement hydration or increase the demand for chemical admixture.

When particles are appropriately dispersed in the mix, the larger fineness of the recycled powder implies advantages regarding strength development. Quan and

Kasami (2018) found that very fine recycled powder (d10/50/90 = 1.7/4.1/18.0) can compensate more than enough for the dilution effect. They obtained a higher compressive strength of SCC when using recycled powder than when using limestone powder. SCC containing 160 kg/m^3 of recycled powder reached compressive strength values of 65 MPa at 28 days. It is surely a clear support for the technical feasibility of using recycled powder in the production of SCC.

Conversely, Quan and Kasami (2018) also reported increased demand for superplasticizer with increasing contents of that very fine recycled powder. This demand was up to three times higher than the required for producing SCC using ground slag or ground limestone as the mineral admixture. Although the main reason was the porosity of the recycled particles, their angularity also contributed to reducing the fluidifying effect of the superplasticizer. This is a significant inconvenience as it increases the production cost significantly, at the time it also reduces the ecoefficiency of this application in relation to the significant environmental impacts of the chemical admixtures.

Duan et al. (2020) used a bit higher recycled powder contents (61.5 and 123 kg/m^3) to produce SCC. They reported consistent results considering the higher recycled powder contents. The decrease in viscosity did not impede to achieve excellent flowability. Regarding the resulting properties in the hardened state, reduced durable performance was reported, as a more porous matrix favors mass transport. The authors relate this outcome to the dilution effect of the recycled powder, and the higher possibility of particle agglomeration with the higher recycled powder content.

Laurente et al. (2016b) produced SCC with high contents of GFRA (114 and 212 kg/m^3), replacing 50% and 100% of the limestone filler in the mix by GFRA (particle size distribution d10/50/90 = 1.2/14.2/67.8 μm). Concrete proportions were the ones in Table 3.5.

Results regarding the self-compatibility of mixtures, evaluated using the total spread (D_f) and spreading time (T_{50}), and the passage ability, evaluated in the V-

Table 3.5 Self-compacting concrete proportioning (kg/m^3).

Materials	HAC0	HAC50	HAC100
Water	170	168	193
CEM II/B	330	326	343
Limestone powder	213	106	0
GFRA	0	114	212
Sand	815	810	767
Crushed granite 6/12 mm	810	506	763
Superplasticizer	2.5	3.2	3.7
w/c	0.52	0.52	0.56

GFRA, Ground fine recycled concrete aggregate.
Source: Modified from Laurente, R., Zega, C. J., & Villagrán Zaccardi, Y. A. (2016b). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VII Congreso Internacional de la AATH* (pp. 1−8). AATH.

Table 3.6 Self-compacting properties of mixes.

Mix	T_{50} (s)	D_f (cm)	T_v (s)
HAC0	4.06	69.5	7.33
HAC50	2.90	61.0	5.73
HAC100	2.43	58.0	4.77

Source: Modified from Laurente, R., Zega, C.J., & Villagrán Zaccardi, Y. A. (2016b). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VII Congreso Internacional de la AATH* (pp. 1–8). AATH.

funnel (T_v), are shown in Table 3.6 (Laurente et al., 2016b). Again, a detrimental effect of recycled powder in self-compactability of mixes was noticed, with less viscosity and cohesion as GFRA increased. The GFRA had greater water affinity than the limestone filler due to its content of calcium silicate hydrates (Hansen, 1986). Moreover, increased water content in mixes was necessary to compensate for the water absorption of the GFRA in comparison with the limestone filler.

Similar to previous studies, Laurente et al. (2016b) showed that, after 28 days of curing, though compressive strength of concrete remained unaffected by the content of recycled powder, water transport and porous properties of concrete showed a detrimental effect of the recycled powder used as filler. Table 3.7 shows similar values for the compressive strength (15 × 30 cylinders), a decrease for electrical resistivity in the saturated condition and water penetration under pressure (IRAM, 1983), and increases in water absorption, capillary absorption rate (IRAM, 2004), and drying rate. Similar results were presented in Kim and Choi (2012) concerning the values of capillary water absorption of mortars that increased with the content of recycled powder in relation to its limited contribution to microstructure development. However, all these effects are not significant, and they prove the technical feasibility of using recycled powder in the production of SCC. Additional research seems still necessary for analyzing the commercial viability of the application, as well as the design optimization and compatibility with chemical admixtures.

3.6 Conclusions

The use of recycled powder is an opportunity for the valorization of waste concrete and a need for its full recovery. Especially for the fraction with particle size below 2 mm of recycled aggregate, obtained from primary crushing of waste concrete, recent investigations have provided new potential applications.

Despite anhydrous cement content is potentially present in waste concrete, studies of recycled powder, obtained from sieving fine recycled aggregate or from grinding it, did not show a noteworthy contribution of anhydrous phases in the recycled powder to microstructure development of mortar or concrete made with it. Moreover, no contribution to the cement efficiency of mixes containing recycled powder has been documented. Therefore the untreated recycled powder must be regarded as an inert admixture unless there is a significant content of clay waste included in it.

Table 3.7 Properties of mixes in the hardened state after 28 days of curing.

Mixes	Compressive strength (MPa)	Density (g/cm^3)	Water absorption (%)		Electrical resistivity (kΩ cm)		Capillary absorption rate (g/m$^2 \cdot$ seg$^{-0.5}$)	Drying rate (g/m$^2 \cdot$ seg$^{-0.5}$)	Average water penetration under pressure (mm)
			By immersion	By capillarity	Saturated by immersion	Saturated by capillary rise			
HAC0	36.6	2.25	6.5	4.2	8.37	10.15	8.12	3.44	33
HAC50	34.5	2.22	7.0	4.7	6.67	7.63	9.44	3.95	27
HAC100	36.0	2.23	6.9	4.5	6.08	7.71	7.89	3.74	22

Source: Modified from Laurente, R., Zega, C.J., & Villagrán Zaccardi, Y. A. (2016b). Agregado fino reciclado molido como fino para la elaboración de hormigones autocompactantes. In: *Memorias VII Congreso Internacional de la AATH* (pp. 1–8). AATH.

The fineness of recycled powder is a critical aspect governing its effect on cementitious mixes. The recycled powder obtained from sieving fine recycled aggregate has a greater porosity than recycled powder obtained from grinding it. The effect of the recycled powder on the water demand and setting time depends on the fineness, porosity, and water affinity of the recycled powder. Better properties are achieved when the recycled powder is obtained from grinding coarser particles of waste concrete. Natural aggregates are then incorporated among these fine particles, and they reduce the porosity and water absorption of the recycled powder. However, attention must be paid to the optimal grinding period depending on the hardness of the natural rock contained in the waste concrete. No added value of extended grinding of FRA has been reported, meaning this increased energy consumption does not lead to meaningful improvement in the effect of the recycled powder on the technological properties of cementitious mixes.

Thermal treatments by calcining the recycled powder between 500°C and 800°C have shown some advantages concerning its reactivity due to dehydration of its phases. However, the ecoefficiency of this procedure is still to be confirmed. In this regard, the replacement of about 15% of cement content by thermally activated recycled powder seems to be near the optimal ratio, whereas contents of 25% or 30% might show some dominant dilution effect if the thermal activation is not very effective. Although the calcination of recycled powder increased its contribution to strength development, the sustainable convenience of the most suitable temperature and replacement ratio remain not fully identified.

Among the possible applications of recycled powder in concrete production, its use in SCC seems the most straightforward. Full replacement of limestone powder by recycled powder in the production is feasible, particularly when very fine recycled powder is used. SCCs with suitable properties are possible to be produced with recycled powder, but some issues regarding superplasticizer demand remain unsolved. Therefore additional research is necessary for the optimization of self-compacting mixes for efficient applications, including potential complementation between recycled powder and other mineral admixtures.

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