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Use of granular coal combustion products as aggregates in structural concrete: Effects on properties and recommendations regarding mix design

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Abstract

This review collates the results obtained in more than 100 scientific publications regarding the performance of concrete with granular coal combustion products (GCCP, commonly referred to as coal bottom ash in literature) as a partial substitute for conventional aggregate. The effects of this by-product on the workability, density and mechanical and durability related properties were analysed. Some conclusions and recommendations are provided to facilitate future research. These recommendations include conducting careful assessments of the specific gravity and water absorption properties of GCCP, replacing conventional aggregate by volume, and compensating the water absorption of GCCP. The use of GCCP as an internal curing water reservoir is proposed as the most promising advanced application.

Keywords: Coal bottom ash, CBA; by-product; valorisation; waste integration; water dosage strategy; workability; durability; lightweight concrete; internal curing; database.

Highlights:

- Granular coal combustion products (GCCP) can be used as aggregates in concrete
- GCCP particles are irregular, rough, light and highly water absorbent
- Compensating for the water absorption by GCCP avoids concrete workability drop
- The strength and durability of concrete decrease if high GCCP contents are used
- GCCP reduces the weight of concrete and works as an internal curing water reservoir

1 Introduction

Combustion of coal in power stations throughout the world generates large amounts of different residues (coal combustion residues, CCRs), where fly ash (FA), coal bottom ash (CBA), boiler slag and flue gas desulphurisation (FGD) materials are the most abundant. These products have generally been managed as waste materials and disposed of in landfills. However, they can be used in beneficial alternative applications, where they are referred to as coal combustion products (CCPs) instead of CCRs.

FGD materials are produced via a process that aims to minimise sulphur dioxide (SO_2) emissions from the exhaust gas system of a coal-fired boiler. FGD materials comprise of Ca-SO_x compounds [1] and have been used in several beneficial encapsulated applications in the construction industry, such as in the manufacture of panels, blocks and plasters [2,3]. Fly ash is the finely divided residue produced by the combustion of ground or powdered coal that is transported by flue gases [4]. The powder-sized particles in fly ash are spherical in shape, and they have hydraulic and/or pozzolanic properties, depending on their chemical composition. Fly ash is already a popular product in the concrete industry and it has been used successfully as a supplementary cementitious material for decades. This beneficial use has contributed significantly to the sustainability of concrete by reducing the utilisation of ordinary Portland cement (OPC) in a wide range of applications. The use of fly ash as a partial substitute of OPC has environmental and economic advantages, and it can also improve the technical properties of concrete, especially those related to durability. CBA comprises agglomerated coal ash particles that are too large to be carried in the flue gas [5] so it remains at the bottom of the boiler. CBA is generally referred to with this term when it comes from traditional pulverised coal furnaces, where it is collected following a dry process. However, other residues that are coarser than fly ash residues are produced in various types of furnaces or collected by different methods, such as boiler slag, fluidised bed combustion ash and pond ash [6]. All of these residues are granular in nature and this is the key characteristic related to their utilisation in the construction sector because they can be employed as aggregates in cement-based materials and other applications. Thus, in this review, the popular term "coal bottom ash" (CBA) is avoided and the more general term "granular coal combustion product" (GCCP) is used instead. This term encompasses all the different types of granular coal combustion by-products referred to in scientific studies of replacements for conventional aggregates regardless of the processes involved in their production or collection.

GCCP represents approximately 20% of the total ash produced in coal power stations (the remainder comprises fly ash). GCCP has been used in asphalt paving mixtures and as a base granular material for roads and car parks [2]. The principal beneficial uses of GCCP in the European Union are in reclamation and restoration. However, the encapsulation of GCCP in cement-based materials is rarely practiced. For instance, during 2016, 20% of all the CBA produced in Europe was used to fabricate concrete blocks [3]. In general, the beneficial reuse of CCPs has been increasing in recent years (**Fig. 1**), mainly due to the development of new applications of FGD, but the reused proportion of GCCP has remained constant (**Fig. 2**). This situation has encouraged the development of research works and new applications in the construction field in order to ensure that a higher volume of this by-product is utilised in the future.

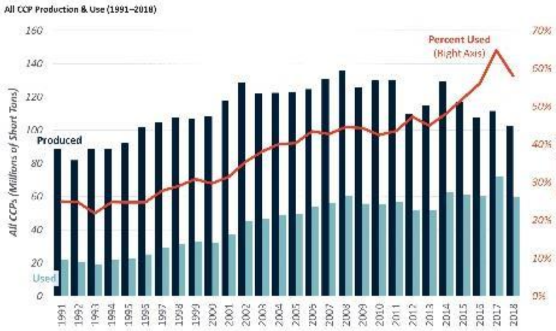


Fig. 1: Changes in the production and use of all CCPs in the USA until 2018 [2].

Fig. 2: Changes in the production and use of CBA in the USA until 2018 [2].

2 Research significance

The use of ground GCCP as a supplementary cementitious material in a similar manner to FA has been suggested in some studies [7,8,17–26,9–16]. The implementation of a highly efficient grinding process in power stations has also been proposed [27]. Furthermore, the manufacture of lightweight aggregates made of pelletised stone dust and ground CBA has been proposed [28]. However, the grinding process consumes energy and the preferred applications would involve using it in a raw form as an aggregate. Studies have explored the use of GCCP as an aggregate in concrete together with other recycled aggregates, such as recycled concrete aggregates [29], granulated blast furnace slag [30,31] and oil palm shell [32].

Several previous reviews have investigated the use of GCCP as an alternative aggregate in concrete [6,33,42–48,34–41]. However, most of these studies mainly considered the pozzolanic activity of GCCP and they generally ignored important aspects related to the nature of the GCCP particles themselves, such as their specific gravity, and aspects of the concrete mix design process, such as the basis on which the conventional aggregate is substituted (by its total volume or weight) or the strategy selected regarding water dosage. In order to consider these parameters, the present review analysed results of the workability, porosity, density, mechanical properties, shrinkage and durability of concrete made with GCCP gathered from more than previous 100 studies. Furthermore, some conclusions and recommendations are provided based on this analysis.

3 GCCP characteristics

The characteristics of GCCP depend on many important variables, such as the coal source, preparation for burning (degree of pulverisation, etc.), the burning process itself (temperatures reached, etc.) and the furnace emptying method (dry or wet) [9,49]. The fact that the characteristics of GCCP depend on many factors during its production make it difficult to quantify the properties of GCCP as aggregates in a precise and general manner. However, representative information from different power stations throughout the world has been reported in scientific articles. The results collated in this review provide broad insights into the ranges, mean, maximum and minimum values for the physical and chemical properties of GCCP particles.

3.1 Physical properties

The appropriate physical characterisation of GCCP is required to assess its performance as an aggregate in any cement-based materials. The size, shape, texture, density and water absorption are the most commonly studied physical properties.

GCCP can contain a wide range of particle sizes, but usually below 20 mm. Particles with a size larger than 4 or 5 mm are discarded when it is used as a fine aggregate, whereas smaller particles are discarded when it is used as a coarse aggregate.

In general, GCCP particles have irregular, disordered, angular or glassy shapes, and a rough or porous texture. These physical characteristics can be observed with the naked eye and by scanning electron microscopy (SEM) (**Fig. 3**). However, some studies described GCCP particles with appearances that deviated from this trend, where they had rounded, regular or spherical shapes [30,31,50–54]. Attempts were made to minimise the roughness and external porosity GCCP particles in some studies by covering them with cement and fly ash paste using a cold-bonding process [55,56].

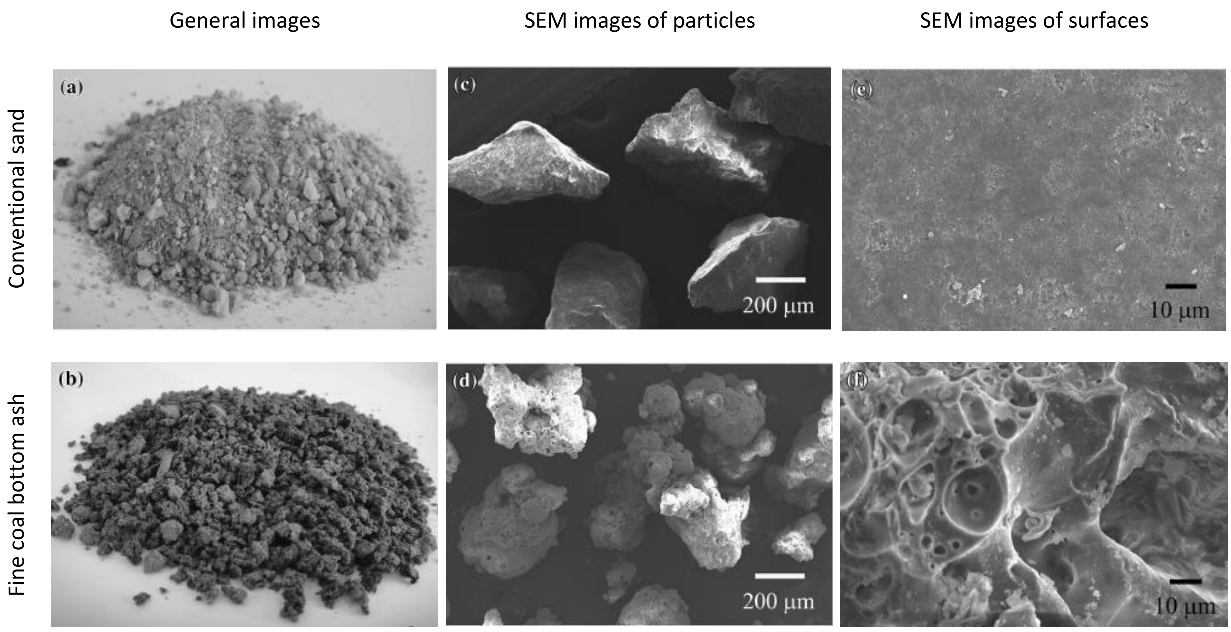


Fig. 3: Appearance of conventional sand and fine coal bottom ash on different scales (based on [57]).

The porous surface indicates that the internal structure of GCCP is porous. Coarse particles may have larger pore volumes than fine particles [56], possibly because the latter can be formed by crushing coarse particles and this process opens their inaccessible porosity. Furthermore, the internal porous structure of GCCP was studied by mercury intrusion porosimetry, which demonstrated that more than one half of the pores were shaped like ink bottles [58].

The porous structure of GCCP results in a lower specific gravity (down to 1 g/cm^3) and higher water absorption capacity (up to 35%) than conventional aggregates. These two properties are illustrated in **Fig. 4** based on several previous studies.

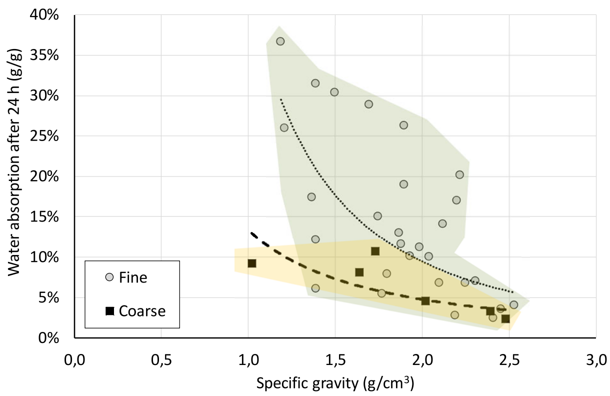


Fig. 4: Relationships between specific gravity and water absorption for GCCP according to several studies [29,30,61–70,31,71–78,50,51,55,57–60].

With the same specific gravity, coarse aggregates exhibit lower water absorption than fine aggregates, probably due to the higher proportion of inaccessible pore volume among the overall porosity in coarse GCCP. However, some fine aggregates exhibit similar performance to coarse aggregates, possibly because of the remaining highly inaccessible pore volume or differences in the characterisation procedure employed. The critical step when determining the specific gravity and water absorption is drying the particles after wetting to reach a saturated surface dry condition. Different methods can be used for this purpose but they may lead to substantially different results, especially when testing lightweight aggregates. For instance, a paper towel-based method [79] leads to higher water absorption and lower specific gravity values than other standard methods where the particles are exposed to a gentle current of warm air in order to reach a saturated surface dry condition [80,81]. The latter methods are considered to lead to underestimates of these properties [82].

The water absorption kinetics is also distinctive for GCCP. They are described by a curve with a steep slope during the first minutes, before stabilising after 5 min (**Fig. 5**), 10 min [58] or 20 min [64]. GCCP exhibit more rapid water absorption than conventional aggregates and other highly absorptive alternative aggregates such as expanded shale (**Fig. 6**).

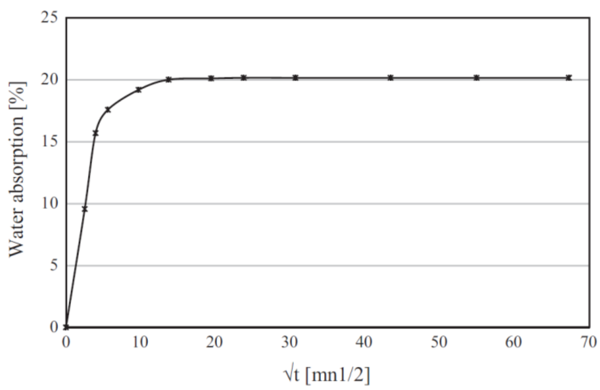


Fig. 5: GCCP water absorption kinetics [63].

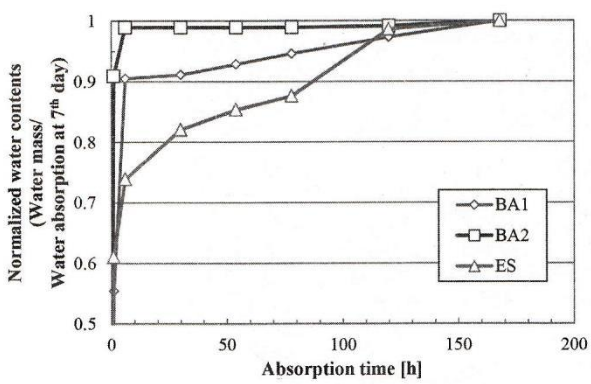


Fig. 6: Normalised water absorption kinetics of GCCP [68].

The high porosity and pore size in GCCP also result in a high desorption capacity in the air under high relative humidity [55,58]. The results obtained by a conventional desorption test in the air at different levels of humidity are plotted in **Fig. 7**. An alternative test was proposed based on the desorption of ink in cement paste (**Fig. 8**). This test confirmed that the desorption capacity of GCCP can also be high in a cement-based material [68].

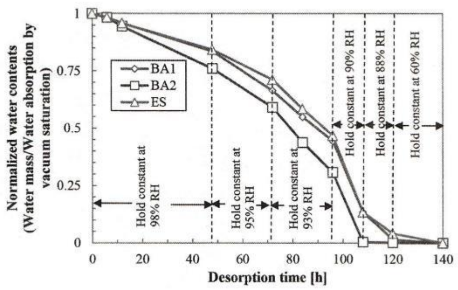


Fig. 7: Normalised water desorption by GCCP during different time periods under various relative humidity levels [68].

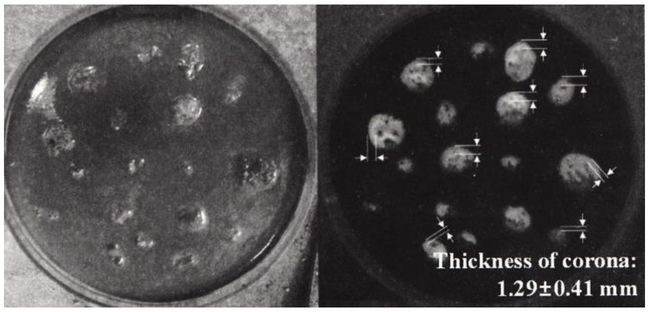


Fig. 8: Desorption of ink in cement paste [68].

3.2 Chemical composition

The chemical composition of any coal combustion product is critically influenced by the coal source [50] and by the burning process to a lesser extent [49]. The most common chemical elements in GCCP are silicon (Si), aluminium (Al), iron (Fe) and calcium (Ca), which coexist with some minor elements such as magnesium (Mg), sodium (Na) and potassium (K). Their mass proportions (in oxide form) in the total incombustible material according to different studies are shown in **Fig. 9**.

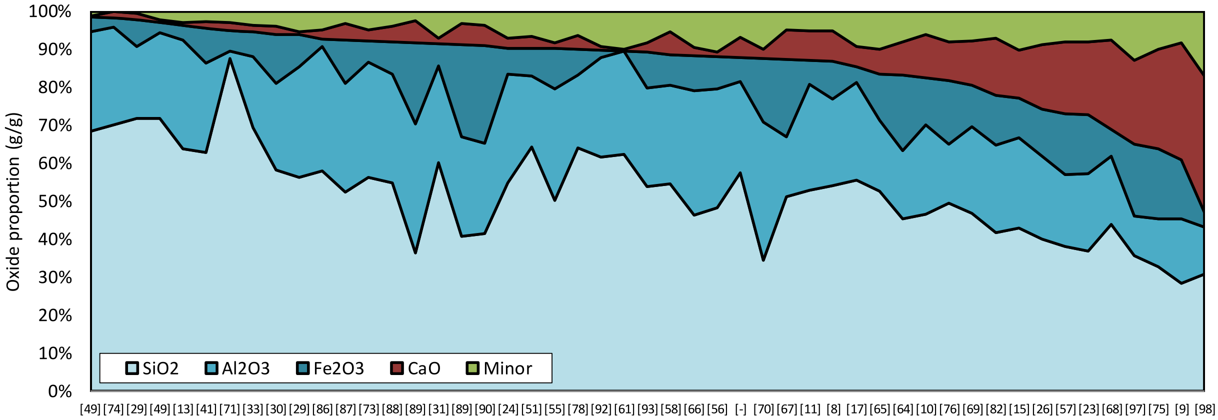


Fig. 9: Chemical composition of GCCP in various studies [8,13,29–31,49,51,56–58,60,63,14,67–71,73,75–78,16,83–92,17,93–98,18,19,21,23,25].

The loss on ignition usually accounts for less than 6% of the composition of GCCP, which is the limit established by American Society for Testing and Materials (ASTM) standard C618 for coal fly ash. This standard also provides a classification for fly ash based on its chemical composition, which could be applied to GCCP. For instance, Class F refers to ashes where the sum of SiO_2, Al_2O_3 and Fe_2O_3 exceeds 70% of the total composition, whereas Class C denotes ashes where the sum ranges between 50% and 70%. Most of the samples considered in this study can be classified as Class F, but a small minority belong to Class C. In addition, according to ASTM C618, Class F ash is usually produced by burning anthracite or bituminous coal, whereas Class C ash is generally produced by burning lignite or sub-bituminous coal [4].

Some of the chemical elements present in GCCP are combined to form crystalline compounds. Various analyses conducted using X-ray diffraction indicate that the most frequent crystalline compounds are quartz (SiO_2) and mullite ($Al_6Si_2O_{13}$). Some examples are shown in **Fig. 10**.

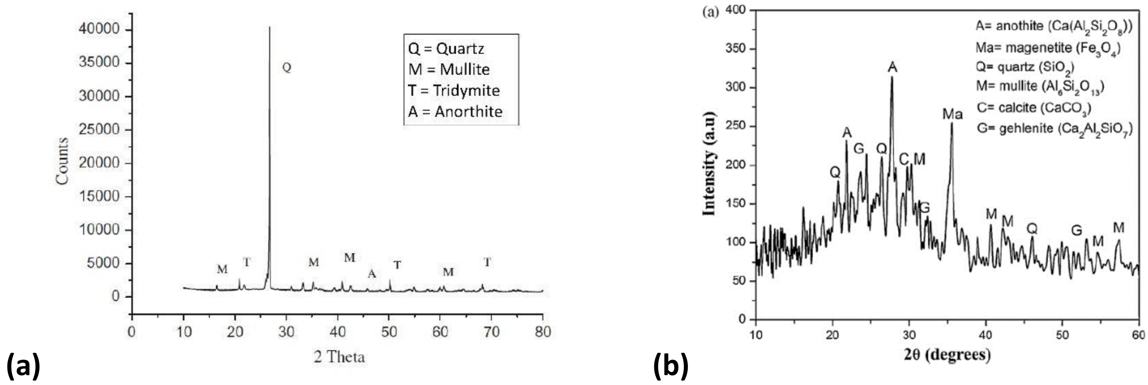


Fig. 10: X-ray diffraction spectra obtained for GCCPs with chemical compositions homologous to (a) Class C [23] and (b) Class F [99].

Some of the minor elements present in GCCP can cause environmental problems, particularly cobalt (Co), manganese (Mn) and other heavy metals. Some works have concluded that the leaching risk for these elements from concrete containing GCCP is low [66,75,100]. However, it must be noted that some cases of toxic leaching have been reported in unlined landfills and surface impoundments [1], but these were non-encapsulated applications with a higher risk.

4 Design of structural concrete with GCCP in raw form as an aggregate

Structural concrete is the most common cement-based material in which GCCP is integrated in its raw form. The scope of the present review is limited to this specific application. However, previous studies have focused on the effects of including GCCP in other construction materials, such as roller compacted concrete [101,102], pervious concrete [74,75,91], paving blocks [103,104], masonry units [61,90,105], masonry mortars [73,92,106], grouts [107] and other non-structural materials [71,93,108,109].

Conventional concrete is the most popular subtype of structural concrete considered in previous studies. Furthermore, different types of high performance concrete, self-compacting concrete and fibre-reinforced concrete have been investigated. The approximate ranges of the structural concrete mix proportions reported previously are presented in **Table 1**. Experimental programs based on the concrete mortar phase obtained conclusions that are valid for concrete. Those mortars usually contain approximately twice the amount of binder and half the aggregate to paste ratio compared to the proportions of concrete.

Table 1: Common ranges for mix proportions of cement-based materials with GCCP as a partial aggregate substitute

	Conventional Concrete*	High Performance Concrete [30,55,58,72,94,110,111]	Self-Compacting Concrete [83,84,96,112,113]
Binder dosage (kg/m^3)	400 ±100	525**	525
Water to binder ratio (g/g)	0.50 ±0.15	0.30	0.40
Paste to aggregate ratio (m^3/m^3)	2.0 ±0.5	2.0	1.5
Coarse to fine aggregate ratio (m^3/m^3)	1.5 ±0.5	1.2	0.7
Most common supplementary cementitious materials	None/ Fly ash	Fly ash + others	Fly ash
Most common admixtures	None	Superplasticizer	Superplasticizer

Common particle size substituted	Fine	Fine	Fine
Common maximum fine aggregate substitution rate	100%	100%	50%

*[32,50,65–67,69,70,85,87,88,95,99,51,114–122,52,54,56,57,60,62,63]

**In some exceptional cases, the binder content is remarkably higher than the indicated value due to the use of supplementary cementitious materials, such as silica fume and ground granulated blast furnace slag [72].

The main conclusion that can be made based on **Table 1** is that no specific proportions have been established for reference concrete in studies of the use of GCCP as an aggregate substitute. It should also be noted that GCCP is commonly used as a fine aggregate, although its use as a coarse aggregate has also been explored [9,72,77].

Conventional aggregate can be substituted by volume or by weight, where the latter option may be simpler to apply because the specific gravity of the particles does not need to be known. Testing the specific gravity of GCCP can be challenging, as stated in Section 3.1. However, substitution by weight distorts the paste to aggregate ratios for GCCP with significantly low densities. Therefore, any conclusions must be treated with caution in this situation.

The water dosage strategy is another fundamental issue that needs to be considered when GCCP is used as a partial conventional aggregate substitute in a concrete mix design. The most common strategies are as follows.

- Constant maintenance of the total water content (=W): GCCP is used in a dry state and its water absorption is not compensated.
- Water absorption compensation (WAC): An amount of water equivalent to the GCCP absorption capacity is added to the mix either with the mixing water or by pre-wetting the GCCP particles.
- Increasing the water content so constant fluidity is achieved (+W): The amount of mixing water is increased when using GCCP in order to obtain the same fluidity as the reference concrete.

5 Properties of structural concrete with GCCP as an aggregate

The performance of concrete containing GCCP is discussed in this section, where the fresh properties, microstructure and density, mechanical properties, volume stability and durability are analysed.

Graphs were prepared by grouping the results obtained from various studies to facilitate a better understanding of the effects of GCCP on concrete. These groupings were based on the water dosage strategy employed and specific gravity of the GCCP. A specific gravity higher than 2.0 g/cm^3 was considered high (H), that between 1.7 and 2.0 g/cm^3 was considered medium (M) and that lower than 1.7 g/cm^3 was considered low (L). The groups were then labelled according to the water dosage strategy and specific gravity classifications. For instance, results obtained for concrete where the total water content was maintained constant when integrating GCCP with a specific gravity higher than 2.0 g/cm^3 were assigned to the grouping of "=W H". The results obtained in studies with a different substitution basis criterion (total volume or weight of conventional aggregate) were separated into different graphs when sufficient amount of results were available. For some of the analysed properties, results for all the possible combinations between the different water dosage strategies and the specific gravity ranges could not be found in literature. In those cases, more research should be developed in order to fully understand the influence of these parameters.

5.1 Fresh properties

The fluidity of concrete decreases when the GCCP content increases and the =W strategy is applied (**Fig. 11**), mainly due to the high water absorption capacity of GCCP. However, the decrease in the workability can be slight when using a highly viscous paste with a low water to binder ratio and high amounts of supplementary cementitious materials [72]. Under these conditions, it is difficult for the mixing water to be absorbed by the GCCP particles. When the WAC strategy is applied, higher fluidity was obtained in some studies, whereas others achieved lower fluidity than the baseline mix (**Fig. 11**). These discrepancies were caused by the difficulty of precisely determining the water absorption by particles (as explained in Section 3.1). The workability may decrease if this characteristic of the particles is underestimated due to ongoing absorption in the fresh state, so the mixing water content is reduced. In contrast, water desorption from pre-wetted particles or insufficient absorption can increase the fluidity when the GCCP water absorption capacity is overestimated. In addition to the effects of the selected water dosage strategy, the irregular shape of GCCP contributes to reducing the workability of concrete. Furthermore, it was reported that the fluidity increased when using rounded GCCP [51] (these results are not included in **Fig. 11**).

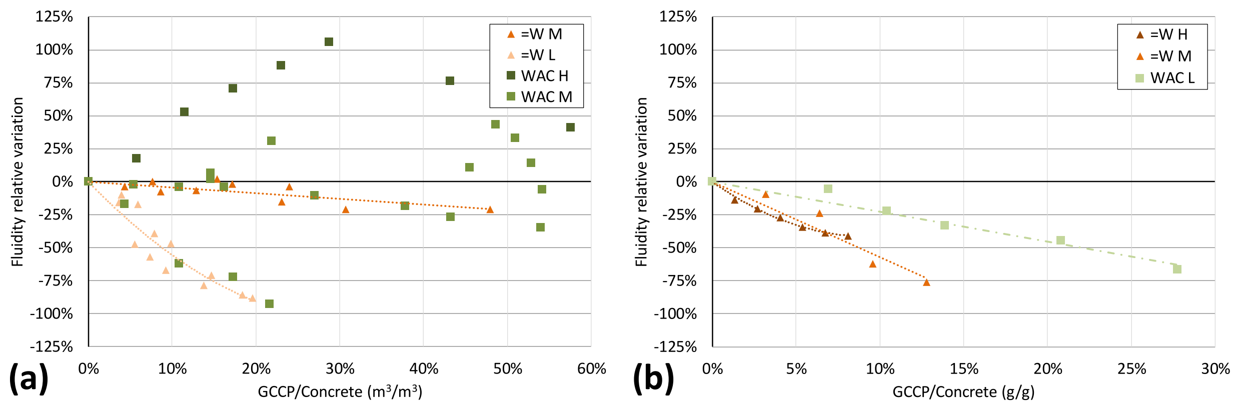


Fig. 11: Relative variations in the fluidity when replacing conventional aggregate with GCCP by volume (a) [51,55,115,56,57,60,63,68,72,85,94] and by weight (b) [62,65,119].

The segregation risk also decreases in self-compacting concretes when incorporating GCCP without compensating for its water absorption [96,112]. Bleeding follows a similar trend to fluidity, where it increases when extra mixing water is added to compensate for water absorption by the GCCP [62,70,123], whereas it decreases without compensation for the water absorption by the GCCP [36,115]. Another important property related to the workability of concrete is its setting time, where GCCP can result in slightly longer initial and final setting times compared with the reference concrete [70].

5.2 Microstructure and density

GCCP is a porous material and it interacts with the paste in different ways depending on the water dosage strategy employed. This interaction can make the porosity of the paste increase or decrease, which usually has a detrimental effect.

In general, the number of pore spaces increases in the concrete paste as the GCCP content increases (**Fig. 12** & **Fig. 13**). This effect is more remarkable if the +W strategy is used [57,63], as well as when the WAC strategy is employed and the excessively pre-wetted GCCP desorbs water while mixing [63,94]. The water to binder ratio increases in both cases.

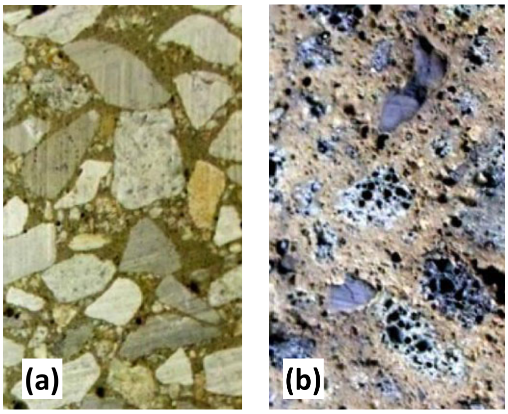


Fig. 12: Cut surface of a geopolymer without GCCP (a) and with all its aggregates substituted by GCCP [77].

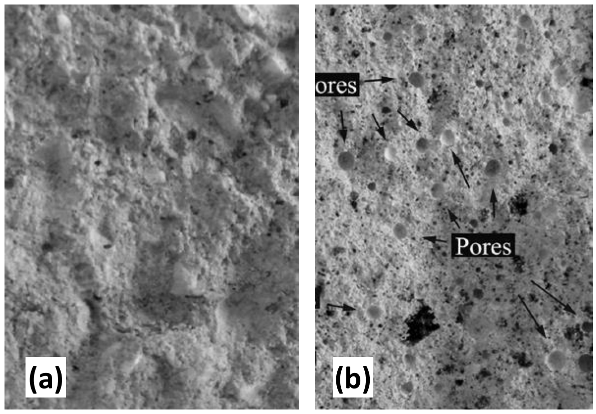


Fig. 13: Fracture surface of mortar without GCCP (a) and with all the sand substituted by GCCP (b) [57].

By contrast, if the =W strategy is used, the absorption of water by the GCCP reduces the water to cement ratio in the paste reducing the porosity of the concrete [87]. However, this phenomenon can also have another effect, as reported in some studies [57,72]. When the GCCP absorbs water, the pores in its particles release air bubbles. These bubbles remain in the concrete if the paste fluidity is not sufficiently high or adequate compaction is not applied, and thus they can migrate to the surface of the material. This process increases the paste porosity but does not increase the concrete porosity because the pore volume only changes its location from the aggregate to the paste. Furthermore, the increase in the paste viscosity caused by water absorption by the GCCP can hinder concrete compaction and promote air entrapment as a consequence [87]. However, the convenient penetration of the paste into the GCCP macro-pores, i.e., good interlocking, has been detected when the paste is sufficiently fluid (**Fig. 14**). It should be noted that the promotion of interlocking might not occur if the GCCP particles are rounded in shape [50].

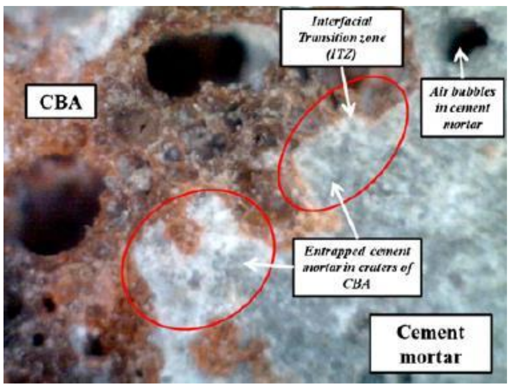


Fig. 14: Cross section of hardened concrete with CBA [72].

All of the phenomena mentioned above modify the porosity of concrete via physical interactions, but chemical interactions have also been found in some studies. For instance, the desorption of water by GCCP particles after setting can contribute to paste densification due to sustained cement hydration and pozzolanic reactions, particularly in the interfacial transition zone because of the presence of reactive silica on the surface of the GCCP (**Fig. 15**). However, a poor quality interfacial transition zone has also been detected [62].

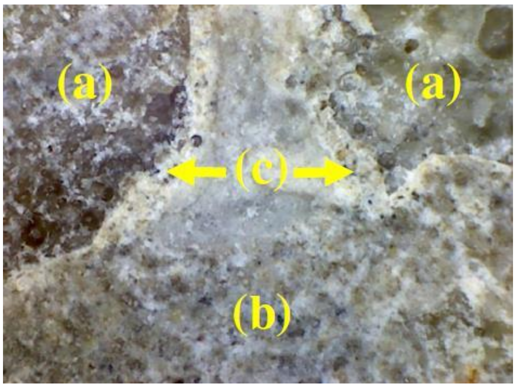


Fig. 15: Microscopic image of the interface between a bottom ash aggregate and cement paste at 200× magnification [114]. The interface between (a) the bottom ash aggregate and (b) cement paste is densified by (c) gel products due to pozzolanic reactions.

The density of concrete decreased as the GCCP content increased in all of the studies considered. The main factor that governs the reduction in the density of concrete appears to be the specific gravity of GCCP. No significant differences were found between concretes produced with or without compensating for the absorption of water (**Fig. 16 a**). However, the +W strategy caused higher reductions in the density (**Fig. 16 b**).

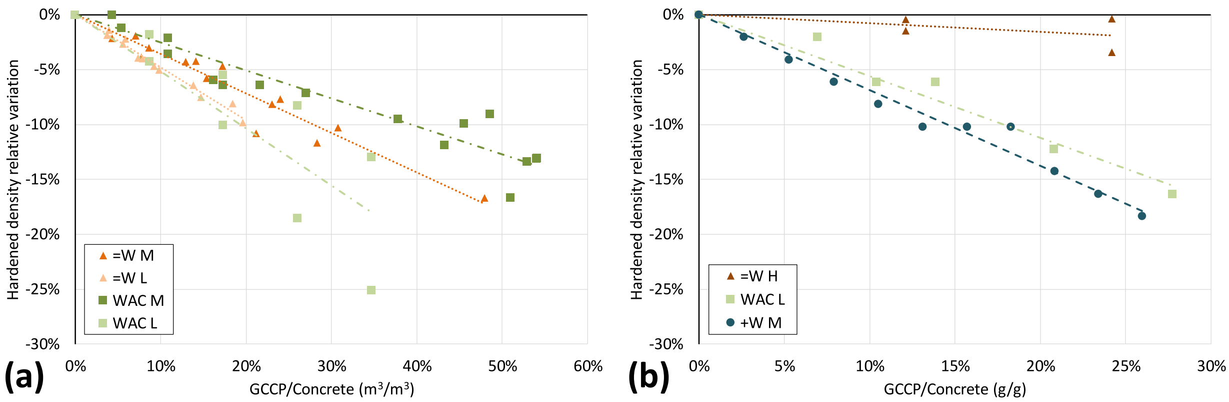


Fig. 16: Relative variations in the density when replacing conventional aggregate with GCCP by volume (a) [57,63,67,72,85,86,94,115] and by weight (b) [9,50,62,87,112].

The effects of GCCP on the microstructure, porosity and density of concrete directly influence its mechanical properties, volume stability and durability, as discussed in Sections 5.3, 5.4 and 5.5.

5.3 Mechanical properties

The basic mechanical properties of concrete, i.e., compressive, splitting-tensile and flexural strength and modulus of elasticity, generally decrease as the GCCP content increases. However, negligible reductions were obtained at low substitution rates (< 25%) and higher values were even determined in some studies (**Fig. 17a & Fig. 17b**).

The decreases in the compressive strength are more pronounced when GCCP with a lower specific gravity is used because a smaller particle density normally implies lower particle strength according to many studies [57,62,87,96]. However, the water dosage strategy is also important because of its influence on the paste properties [62,94]. The application of the +W strategy clearly aggravates the decrease in the strength, whereas no great differences are found between concrete produced using the =W or WAC strategies. Substitution by weight boosts any effect on strength because it implies an increase in the total aggregate content (**Fig. 17b**). The effects of the characteristics of the interfacial transition zone on the mechanical properties are difficult to evaluate. Some studies have suggested that they contribute to the densification of concrete (see Section 5.2), but this effect might be minor compared with the other negative effects of GCCP on concrete.

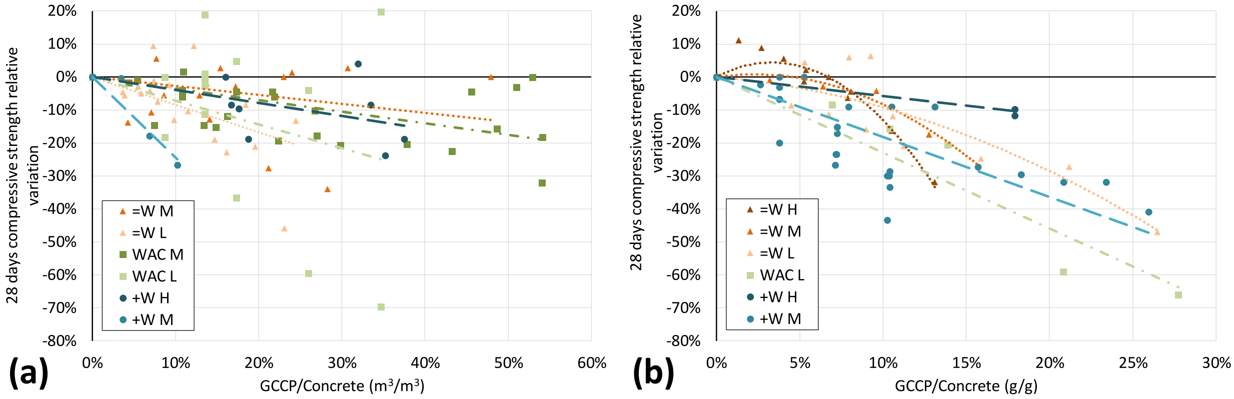


Fig. 17: Relative variations in the 28-day compressive strength when replacing conventional aggregate with GCCP by volume (a) [51,55,85,86,94,95,99,114–116,118,123,57,59,66,67,70,72,78,83] and by weight (b) [9,50,121,124–126,52–54,62,65,88,96,119].

Early strength development, i.e., the $\frac{\text{CS7}}{\text{CS28}}$ ratio, is lower in concrete containing GCCP (**Fig. 18a**), which has been attributed to the existence of late pozzolanic reactions [69,70,121] and hydration sustainment via water desorption (internal curing) [55,127]. The higher water content of mixes produced using the +W strategy also leads to lower strength development during the first 7 days because the higher water to cement ratio delays paste setting and early hardening [128,129]. When a conventional aggregate is substituted by weight, the trends are more difficult to establish because the aggregate to paste ratio is modified (**Fig. 18b**).

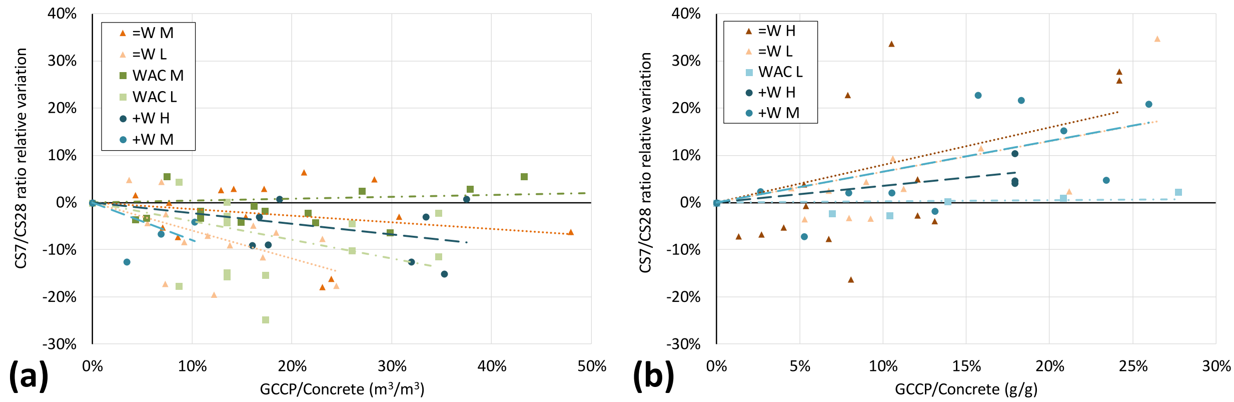


Fig. 18: Relative variations in the 7-day to 28-day compressive strength ratio when replacing conventional aggregate with GCCP by volume (a) [51,57,95,99,115,118,123,130,66,67,70,72,78,83,85,86] and by weight (b) [9,50,125,52,54,62,65,88,96,121,124].

The modulus of elasticity follows a similar trend to the compressive strength, where the modulus of elasticity is lower when the specific gravity of the GCCP is lower (**Fig. 19a**). This effect is explained by the usually greater deformability of less dense aggregates. Moreover, the +W strategy has a clear detrimental effect. These trends are less pronounced when the substitution is applied by weight (**Fig. 19b**). In this case, the stiff conventional aggregates are replaced by weak GCCP, but part of the paste is normally more deformable than the aggregates, and even more than GCCP. Thus, the effect of substitution on the paste counteracts the effect of substitution of the conventional aggregate, thereby resulting in less drastic decreases in elasticity.

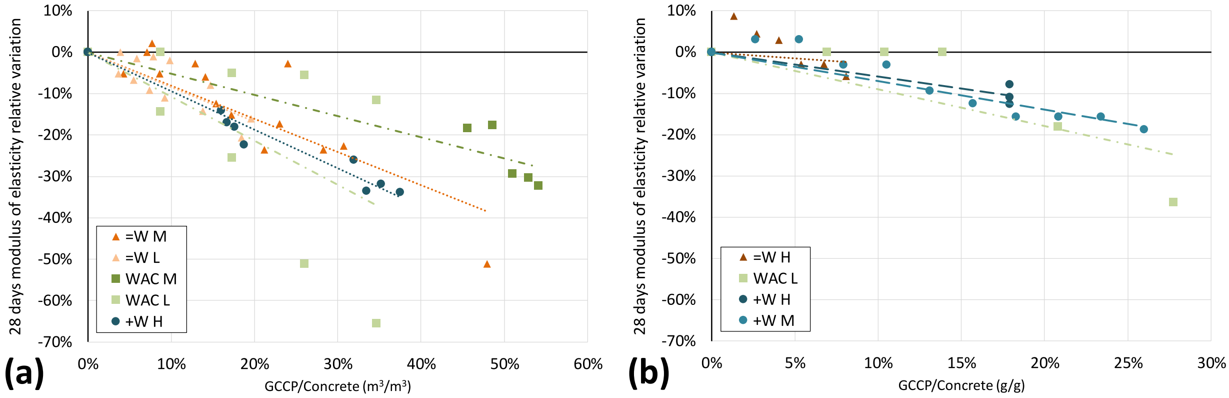


Fig. 19: Relative variations in modulus of elasticity when replacing conventional aggregate with GCCP by volume (a) [59,67,118,70,72,85,86,94,99,115,116] and by weight (b) [50,62,65,121,124].

In general, the splitting-tensile and flexural strength of concrete decrease when incorporating GCCP (**Fig. 20** and **Fig. 21**). However, some studies found performance improvements, possibly due to better paste quality because of the occurrence of pozzolanic reactions [65] or to the blockage of cracks because of the presence of pores in the paste of bottom ash concrete [115]. GCCP particles with a lower specific gravity yield worse results. Furthermore, the effect of the water dosage strategy might not be the same as that on the compressive strength. In particular, it seems that the +W strategy leads to higher flexural strength than the =W strategy.

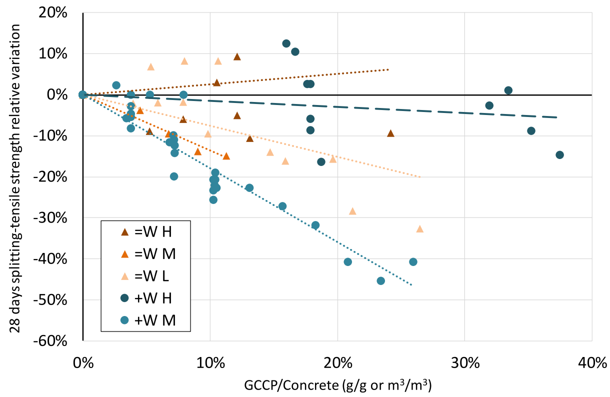


Fig. 20: Relative variations in 28-day splitting-tensile strength when replacing conventional aggregate by GCCP [9,50,125,126,52,54,69,70,83,85,120,121].

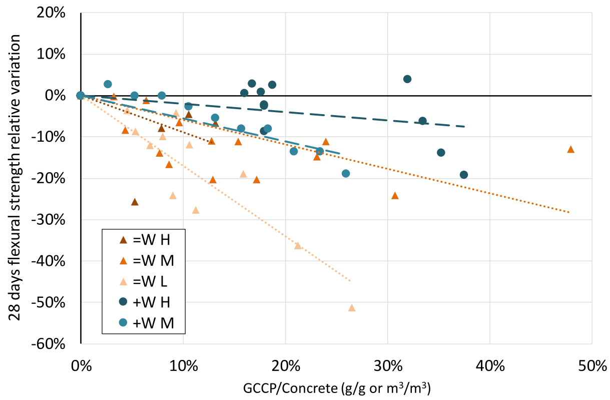


Fig. 21: Relative variations in 28-day flexural strength when replacing conventional aggregate by GCCP [50,52,54,69,70,72,119,121,124,125].

The wear resistance decreases when GCCP is integrated in concrete (**Fig. 22** & **Fig. 23**) because of its lower strength compared with conventional aggregates and the effects of water absorption or desorption on the paste quality [70,85,111,116].

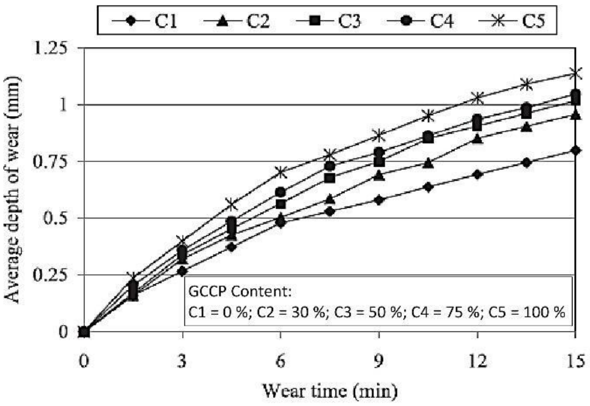


Fig. 22: Depth of wear (mm) [116].

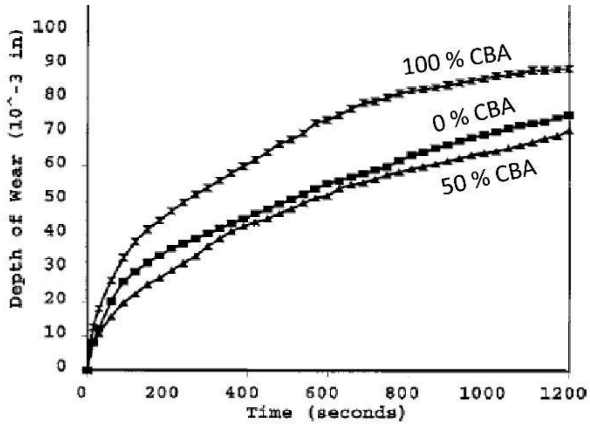


Fig. 23: Depth of wear (10^-3 in) [70].

5.4 Volume stability

Different types of shrinkage can be affected when GCCP is integrated in concrete. Any deformation might be boosted because of the presumably lower elasticity of GCCP particles, but some reductions can occur depending on the water dosage strategy selected. For instance, autogenous shrinkage decreases if compensation for water absorption is implemented [55,78], as it can be seen in **Fig. 24**. Furthermore, a higher water loss is registered in air-drying conditions if the selected water dosage strategy increases the total amount of water in the concrete. This water loss leads to drying shrinkage. Therefore, greater shrinkage is generally found in air-drying conditions when using GCCP [70,78,96,115,118,123]. However, autogenous and drying shrinkage can coexist in air-drying conditions depending on the concrete water to cement ratio, environmental humidity and size and shape of the specimens. Therefore, compensation effects have led to decreased shrinkage in some studies [58,60,95,99,123]. Some examples of the different shrinkage results obtained in air-drying conditions are shown in **Fig. 25** and **Fig. 26**. Finally, concrete absorbs more water when the GCCP content is higher (see Section 5.5.1), thereby leading to more swelling in water immersion conditions [69,70,78], as shown in **Fig. 27**.

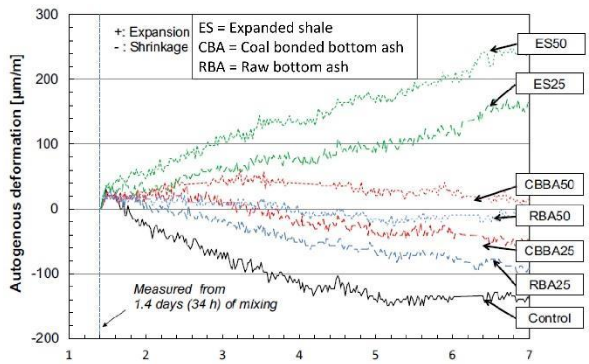


Fig. 24: Autogenous shrinkage [55].

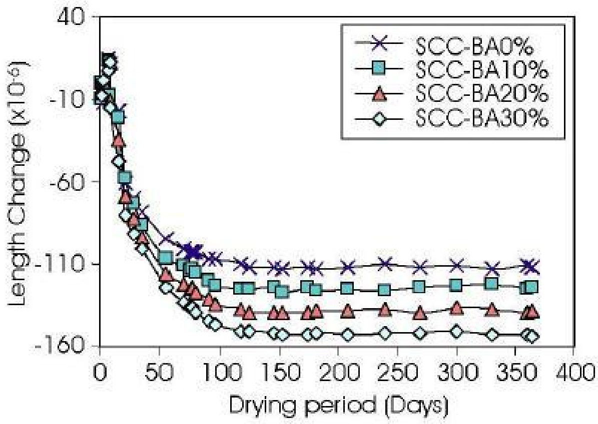


Fig. 25: Shrinkage in air-drying curing conditions [96].

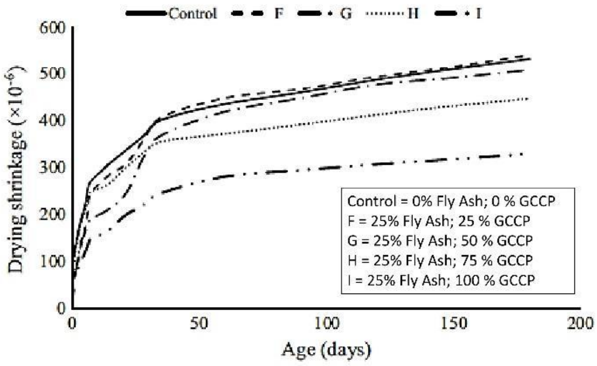


Fig. 26: Shrinkage in air-drying curing conditions [95].

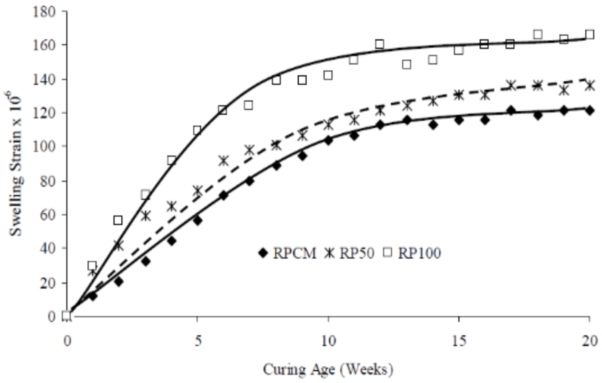


Fig. 27: Swelling [69].

5.5 Durability

Previous studies have focused on durability to obtain important information about the long-term performance of concrete containing GCCP. The permeability and resistance to different harmful external agents are the properties investigated most frequently.

5.5.1 Permeability and absorption

The higher porosity of GCCP concrete leads to greater permeability to any external agent. For instance, the use of GCCP results in higher gas permeability [63] and this can lead to a higher carbonation depth (**Fig. 28**). The increased porosity due to the inclusion of GCCP also enhances the capillary water uptake [85,111,115,116] and water penetration [50]. However, results similar to the reference are obtained with low substitution rates (**Fig. 29** & **Fig. 30**).

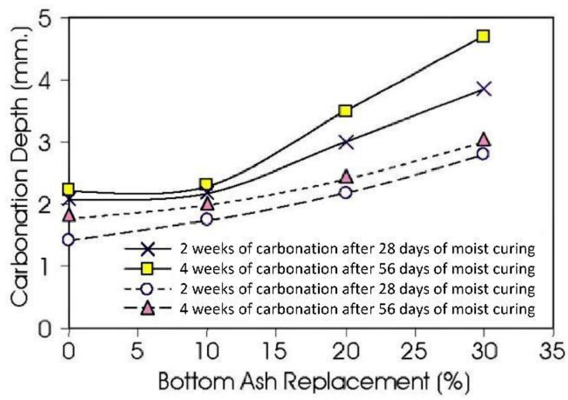
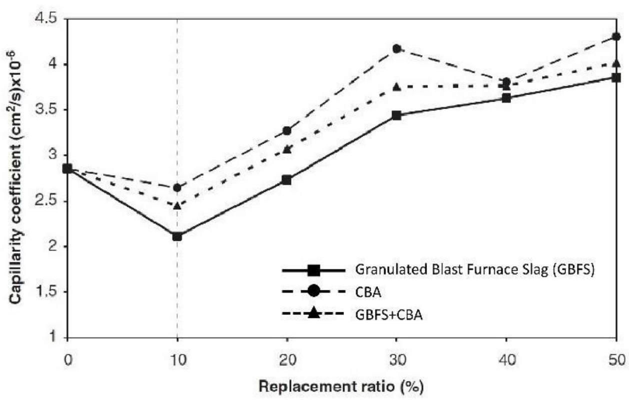


Fig. 28: Carbonation depth [96].



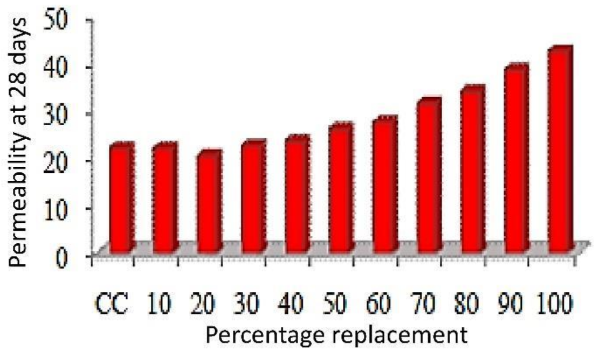


Fig. 29: Water absorption by capillary action [111].

Fig. 30: Water penetration [50].

T e water absorption of concrete with GCCP is higher than the absorption of the conventional concrete, especially when the specific gravity of the GCCP employed is low (**Fig. 31**). If the =W st ategy is applied, the lower water to cement ratio results in a denser paste and lower water bsorption. Imperfect aggregate to paste interlocking can contribute to greater porosity and w ter absorption. Furthermore, a potential relationship can be established between a cement-b sed material and its water absorption, which might differ depending on the paste content (**Fig. 32**).

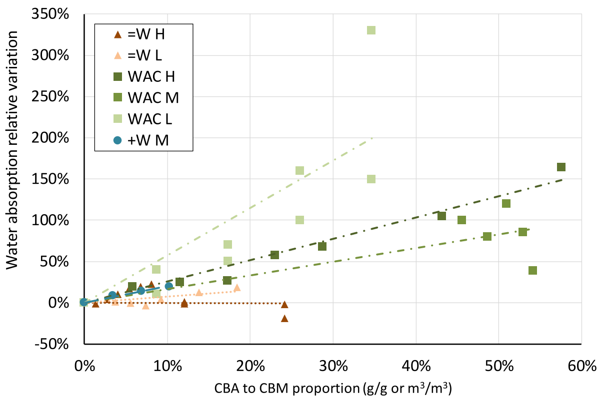


Fig. 31: Relative variations in water absorption when replacing conventional aggregate by GCCP [9,63,65,83,86,94,99,115,116],

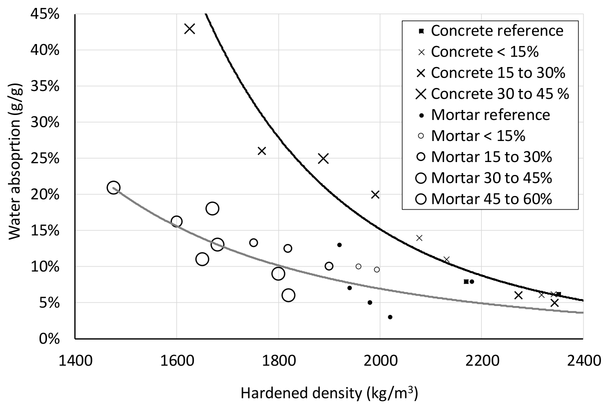


Fig. 32: Relationship between hardened density and water absorption for cement-based materials with different GCCP contents [9,63,86,94].

Chloride ion permeability is another durability-related property that is strongly linked with porosity. At early ages, the use of GCCP leads to a significant increase in permeability. However, the differences with various substitution rates tend to decrease over time, and better performance may be obtained using concrete containing GCCP in some cases (**Fig. 33** & **Fig. 34).** These late improvements are explained by paste densification due to internal curing and pozzolanic reactions [96,114].

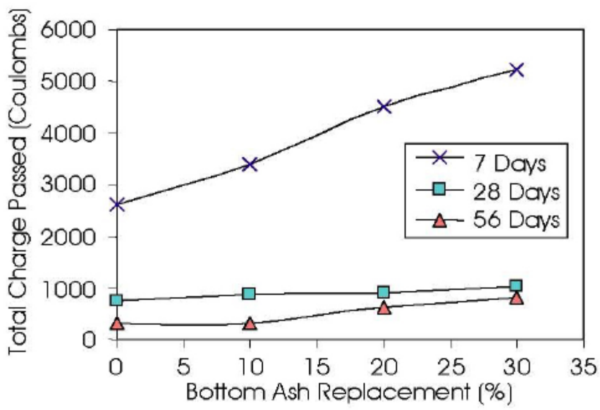


Fig. 33: Chloride ion permeability [96].

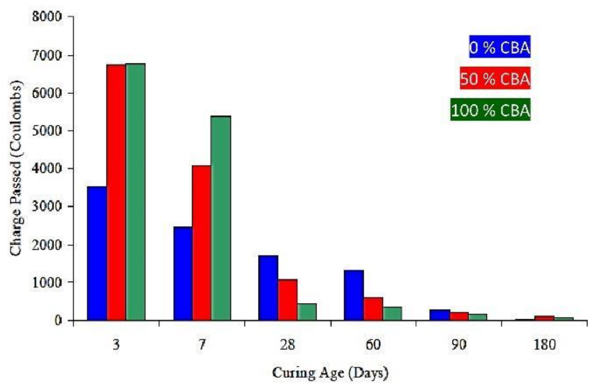


Fig. 34: Chloride ion permeability [69].

5.5.2 Resistance to chemical attacks

In addition to carbon dioxide, water or chloride ions, other external chemical agents can penetrate into concrete and damage it. Contradictory results have been obtained in various studies regarding the effect of the GCCP content on sulphate attack resistance. Higher expansions were detected in some studies [69,70,99], thereby indicating worse performance, whereas others fou d lo er expansions [96]. Examples o both possibilities are sho in **Fig. 35** a d **Fig. 36**.

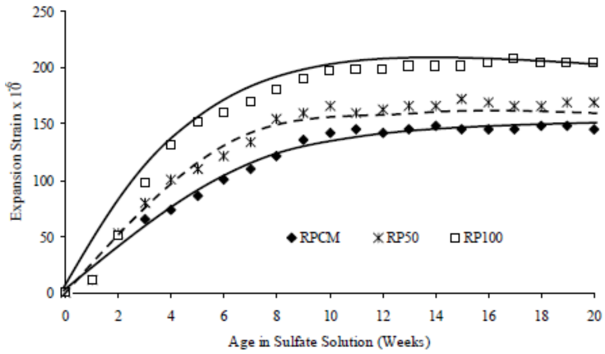


Fig. 35: Expansion of concrete when submerged in a sulphate solution [69].

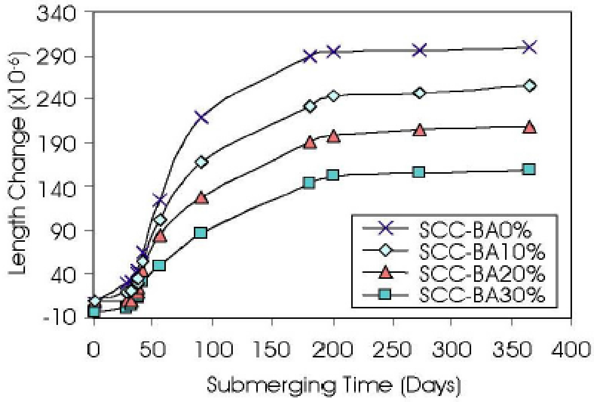


Fig. 36: Expansion of concrete when submerged in a sulphate solution [96].

Similar acid attack resistance performance (**Fig. 37**) or even better (**Fig. 38**) can be obtained by incorporating GCCP in concrete [66][99].

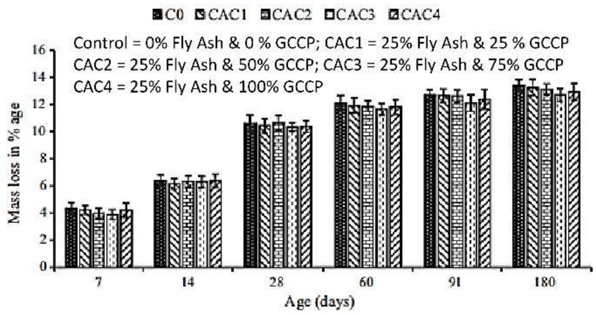


Fig. 37: Mass loss of concrete when submerged in an acid solution [66].

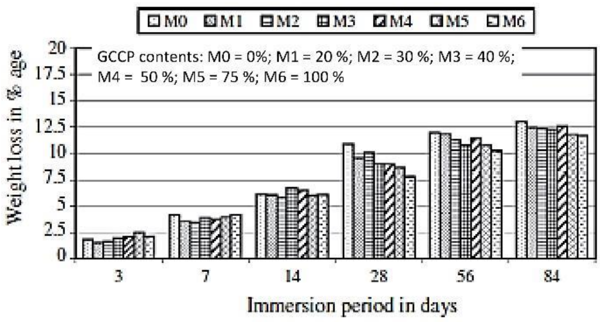
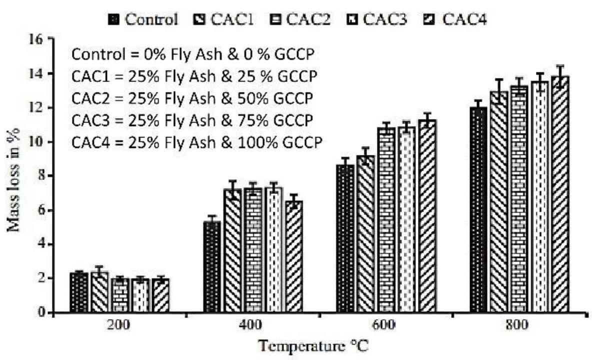


Fig. 38: Mass loss of concrete when submerged in an acid solution [99].

5.5.3 Resistance to exposure to high temperature

GCCP can contain a certain amount of unburnt coal, so concrete produced using this sub-product may respond poorly when subjected to high temperatures (> 800°C), as confirmed by several studies (**Fig. 39**). However, better performance was obtained at low substitution rates in other studies (**Fig. 40**).



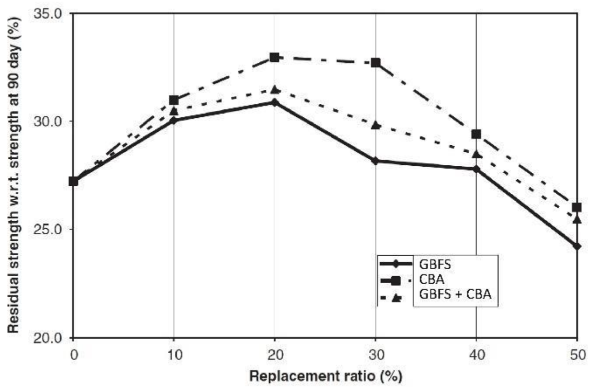


Fig. 39: Mass loss of concrete after exposure to high temperature [66].

Fig. 40: Mass loss of concrete after exposure to high temperature [111].

5.5.4 Resistance to freezing and thawing

The resistance to freezing and thawing decreases when incorporating GCCP [30,69,121]. However, similar results to the reference or acceptable values can be obtained with low substitution rates (**Fig. 41** & **Fig. 42**).

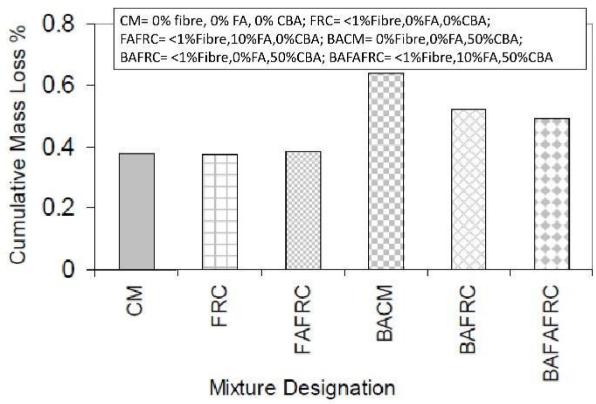


Fig. 41: Cumulative mass loss after 50 freezing and thawing cycles [121].

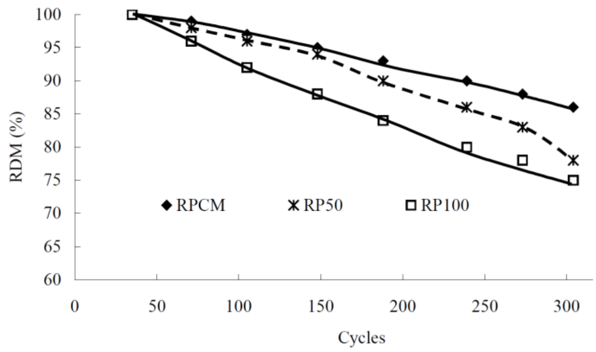


Fig. 42: Decrease in the relative dynamic modulus (RDM) after freezing and thawing cycles [69].

6 Discussion of the applications of concrete with GCCP

The use of GCCP as an alternative aggregate in concrete has important environmental and economic advantages. First, it helps to reduce the consumption of natural and quarry sand. Therefore, the impacts related to the exploitation of these resources are decreased. Less virgin resources are depleted and mining is reduced, which is an activity with high social, environmental and economic costs. Second, the beneficial use of GCCP instead of its management as a waste material reduces the use of landfill space, as well as the risks and costs associated with the disposal process [5]. In addition to these advantages, the integration of GCCP in cement-based materials can potentially improve their technical performance because of its special characteristics. In particular, low specific gravity and a high capacity for water absorption are the most distinctive properties of GCCP, and they allow researchers to propose advanced applications such as lightweight concrete and internally cured high performance concrete.

The low specific gravity of GCCP particles (1.2–2.3 g/cm^3) might be useful for decreasing the weight of concrete by substituting for normal weight conventional aggregates. However, studies suggest that integrating this waste material is rarely sufficient to satisfy the density and compressive strength requirements for lightweight structural concrete (< 2000 kg/m^3 and > 15 MPa, respectively [131]). The requisite conditions can only be satisfied by mixes with the highest GCCP contents or those that include other lightweight aggregates (**Fig. 43**).

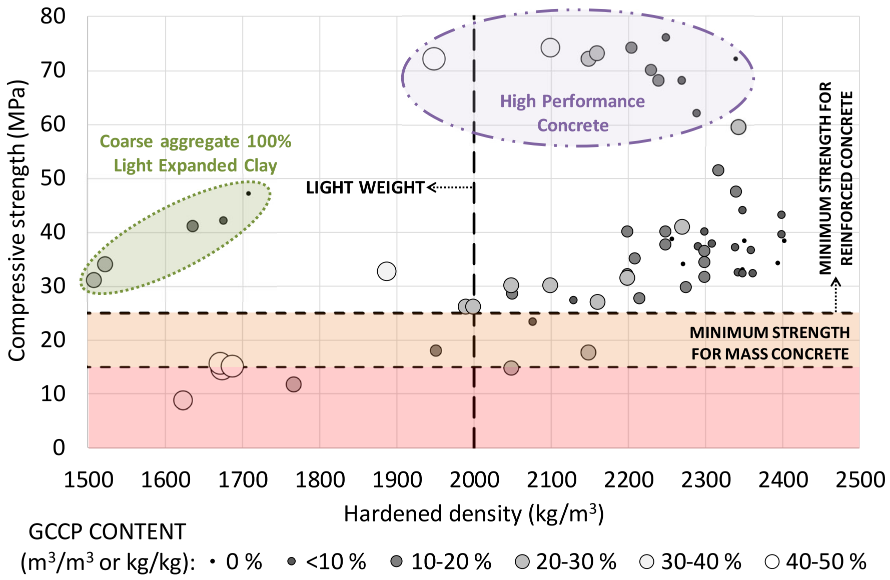


Fig. 43: Relationship between hardened density and compressive strength of concrete with different GCCP contents [9,50,57,62,67,72,77,85,86,115].

In addition, GCCP can be used to improve high performance concrete, which is usually characterised by a low water to binder ratio and it can be affected adversely by considerable autogenous shrinkage. This deformation is the self-created bulk strain generated in cement-based materials during hardening at constant temperature [132] and the driving force responsible is paste self-desiccation [133,134]. One strategy for mitigating paste self-desiccation and reducing autogenous shrinkage is internal curing. ASTM C1761 defines internal curing as the supply of water within a cementitious mixture using pre-wetted lightweight aggregate or other materials that readily release water from within the particles, thereby mitigating self-desiccation and sustaining hydration [135]. The particles that can release water inside concrete are known as internal curing water reservoirs and they can be wet aggregates with high water absorption and desorption capacities. These requirements can generally be satisfied by GCCP (water absorption varies from 5% to 35%), so its use as an internal curing reservoir in high performance concrete is considered to be a promising advanced application [68]. Furthermore, low GCCP contents are sufficient to achieve effective internal curing due to the remarkably high water absorption capacity of GCCP, thereby reducing any detrimental effects on the mechanical properties. Similar to any other internal curing reservoir, GCCP can be wetted before mixing or added dry to the mix so it can absorb water from the concrete paste in the fresh state and then release it after setting. Some studies suggest that these two procedures lead to similar concrete properties [58] but the first method is preferred. The water absorption process is more efficient when the aggregate particles are exposed to water, e.g., by water immersion, compared with that when they are integrated in concrete to absorb water from the paste. Moreover, pre-wetting GCCP allows the wetting process to be extended for a long time so conditions closer to saturation can be achieved. In addition, specific procedures such as vacuum saturation can be applied in a pre-wetting scenario.

Fig. 44 presents the coal combustion products, their distinctive properties, the processes applied for them to be used in different applications, the most common mix design strategies and their effects on the performance of concrete.

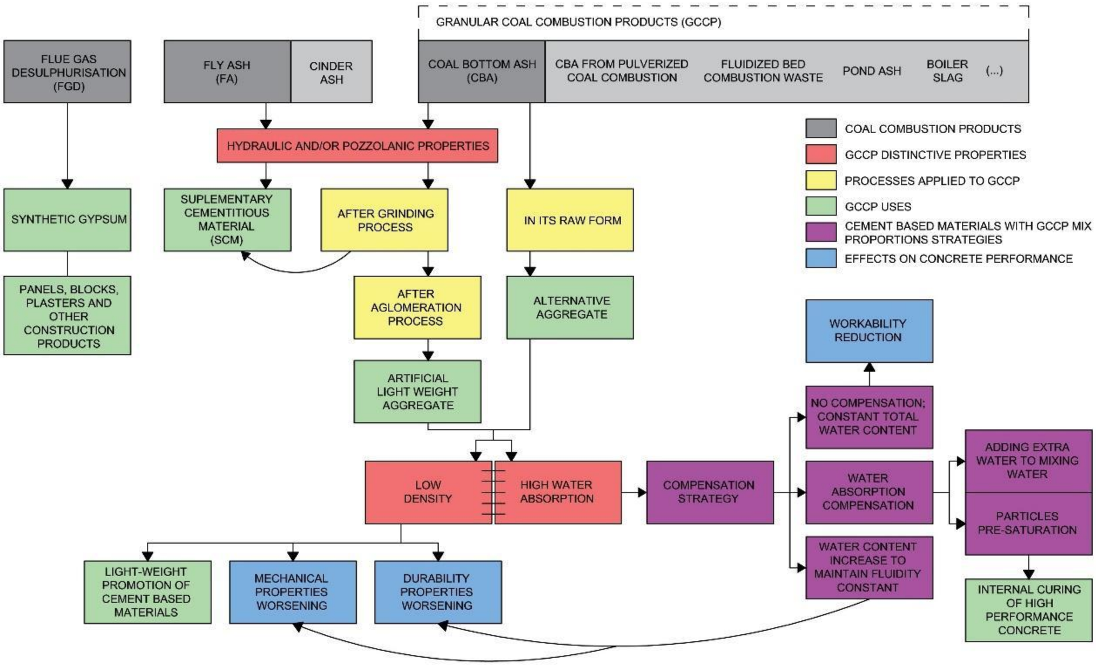


Fig. 44: GCCP in construction and cement-based materials.

To sum up, the comprehensive review of the scientific literature supports the feasibility of integrating GCCP in concrete. The authors-created graphs can help to understand the influence of GCCP in different properties, depending on the water dosage strategy used and the specific gravity of the by-product. The analysis of the collated findings permits to conclude that this by-product can be used to decrease the weight of concrete and also to work as an internal curing water reservoir therefore reducing the self-desiccation of mixes with low water to binder ratios.

7 Conclusions and recommendations

The following conclusions can be drawn based on this analysis of the results obtained in more than 100 studies of the use of GCCP as aggregates in concrete. The general recommendations based on these conclusions may provide useful insights to facilitate future research or field studies.

1. In general, GCCP particles are physically characterised by an irregular shape and rough texture. Moreover, the specific gravity of GCCP, i.e., approximately 1.2 to 2.3 g/cm^3, is lower than that of conventional aggregates and its water absorption capacity (from 5% to 35%) is higher than that of conventional aggregates, with rapid kinetics. These key characteristics must be carefully evaluated before using GCCP as an aggregate in any cement-based material. However, their correct determination is challenging and different procedures can lead to inaccurate results.
2. The chemical composition of GCCP is highly dependent on the coal source, where it mainly comprises silicon (Si), aluminium (Al) and iron (Fe), which can be combined in the forms of quartz and mullite. The presence of reactive silica on the surface of GCCP results in potentially pozzolanic activity. Some minor potentially hazardous elements are also present.
3. GCCP has been used as an aggregate substitute in many different cement-based materials. Conventional concrete is the most popular material but the integration of GCCP is also feasible in different types of high performance and self-compacting concrete. GCCP has mostly been employed as a fine aggregate but descriptions of the use of GCCP as a coarse aggregate have also been reported.

4. The amount of GCCP used in order to replace conventional aggregate should be established based on the volumetric proportion, i.e., by considering its specific gravity. If this method is not used and aggregates are substituted by weight, the concrete aggregate to paste ratio can increase, thereby resulting in reduced workability, strength and durability.
5. The water absorption capacity of GCCP should be considered when designing a concrete mix. Three different water dosage strategies can be employed comprising constant total water content (=W), water absorption compensation (WAC) and water increase so fluidity is maintained constant (+W). Each one has different effects on the properties of concrete, but the second is generally preferred because it does not greatly affect the workability and it avoids modifying the water to cement ratio.
6. If the =W strategy is applied, the workability of concrete decreases because of the ongoing absorption of water by GCCP. If the WAC strategy is applied, the workability can decrease or increase due to underestimation or overestimation of the water absorption capacity. The irregular shape of GCCP also contributes to decreases in workability under any strategy.
7. The porosity of concrete increases with the GCCP content because of the porosity of the particles themselves and the irregularity of the particles that enhances air entrapment.
8. The mechanical properties of concrete containing GCCP are generally worse than those of conventional mixes due to the weakness of the waste particles and detrimental effects on the paste. Worse results are obtained with less dense GCCP and the +W strategy. Low substitution rates lead to slight decreases in strength. Greater late strength development is usually attributed to pozzolanic activity.
9. The water absorption capacity and permeability are greater when the GCCP content is higher. GCCP content also increases drying shrinkage and swelling, but decreases autogenous shrinkage. There is no general agreement regarding other durability-related properties due to the lack of reported results, but some studies indicate that GCCP has only slight negative effects on these properties.

The low density of GCCP may be advantageous for decreasing the weight of any cement-based material. However, lightweight concrete with acceptable strength is difficult to obtain if other conventional lightweight aggregates are not used in combination with GCCP. Nevertheless, the high water absorption and desorption capacities of GCCP mean that it can satisfy the basic requirements for use as an internal curing water reservoir in high performance concrete. Therefore, this is considered one of most promising advanced applications of GCCP in the field of concrete production. Thus, future research efforts should focus on the less well characterised phenomena related to GCCP. In particular, the following issues should be investigated: suitable procedures for determining the specific gravity and water absorption capacity of GCCP (which could be applicable to other lightweight aggregates), further studies of the leaching risk for the minor potentially hazardous elements present in GCCP, and experimental studies of the influence of GCCP on the durability of concrete.

Declaration of Competing Interest

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.

Credit authorship contribution statement

Roberto Rodríguez-Álvaro: Conceptualization, Formal analysis, Investigation, Writing – original draft, Visualization. **Sindy Seara-Paz:** Formal analysis, Investigation, Writing - review & editing, Supervision. **Belén González-Fonteboa:** Formal analysis, Investigation, Writing - review & editing, Supervision. **Fernando Martínez-Abella**: Formal analysis, Investigation, Supervision.

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