

GGBS (Ground-granulated blast-furnace slag), is a by-product of the iron and steel-making industry.

The iron ore, and by consequence, the slag is not a pure product. It contains silica and also a lot of unwanted elements such as copper, lead, nickel, chromium, magnesium, alkali (coming mainly from coal), cobalt, etc. The list is not exhaustive.

In order to remove these unwanted components, the iron ore is mixed, prior to burning, with limestone or quicklime (when limestone is used, more energy is needed in order to convert it into quicklime).

When the ore is smelted, the iron oxide is reduced to metallic iron by the carbon monoxide coming from the semi-combustion of the coke.

The ore “releases” the other components which combine with the quicklime to form several different hydraulic elements such as  $C_2AS$ ,  $C_4AF$ ,  $CS/C_2S/C_3S$  ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) and so on. The mineral composition depends on the temperature reached and of the proximity of the quicklime. This mineralogy is nearly unpredictable. The iron/steel is heavy and “sinks” to the bottom of the furnace while the lighter slag floats on top of the melted steel.

At the bottom of the blast furnace, a decantation takes place. The steel is collected on the lower level, and the slag on a higher level. However, the slag also collects other elements lighter than steel such as sulfide salts ( $FeS$ ,  $MnS$  .....), un-hydrated quicklime, metals or metal oxides and alkali.

After cooling, the slag is fragmented, stored like a cement clinker and then ground into a fine powder.

The first purpose of GGBS addition in a cement concrete is to reduce its porosity in order to make it more resistant to salt aggression. The same goes with lime: it reduces its porosity but, by consequence, reduces dramatically its breathability.

The second purpose of GGBS addition is to reduce the carbon dioxide footprint. However, a closer look at the production may lead to reconsider the stated benefits of this post-industrial product.

Putting aside the tremendous amount of energy required to produce steel, one has to take into consideration the following facts:

- The energy used in the production of quicklime, cooling, transportation to the steel plant and reheating at  $1,500\text{ }^{\circ}\text{C}$  in order to use it in the furnace (the quicklime represents about 35% of the mix) is too often ignored and not counted despite its great impact.
- The production of coke is also a very energy demanding process with undesirable emissions.
- The rapid cooling of the slag, then the fragmentation, then the grinding of this very hard material, requires again a non-negligible amount of energy.

Considering that the slag’s mass represents more than a third of the steel’s mass, its energy usage cannot be ignored and should be taken under consideration.

The use of “pozzolans” has become a trend for some companies pretending to recreate Romans mortars where the use of a combination of lime and pozzolan as aggregate was used on some projects. Today, the ASTM C-1707 tries to define the use of pozzolan and lime for mortars. However, it appears that these “pozzolans” are in fact, in most cases, GGBS. A GGBS is NOT a pozzolan.

A pozzolan is a siliceous or aluminosiliceous material that in itself possesses little or no cementitious value but that in finely divided form and in the presence of moisture will chemically react with alkali and alkaline earth hydroxides at ordinary temperatures to form or assist in forming compound possessing cementitious properties (ASTM C-51).

A GGBS is, contrary to a pozzolan, a hydraulic material with cementitious value. As an example, some cements in Europe contain up to 95% of GGBS.

A GGBS is mainly composed of  $C_xS$  as  $C_3S$ ,  $C_2S$ ,  $CS$  or, under a different mineralogical form ( $\alpha$ ,  $\beta$ ,  $\gamma$ ), of  $C_2AS$ ,  $C_4AF$ . The free silica, which can have a pozzolanic reaction with the lime, generally never goes beyond 1%.

However, we must not forget that the main goal in steel manufacturing operations is to remove the silica from the iron ore by combination with the quicklime.

The free vitreous silica, or silica aluminates like in the Pozzolanic ashes, is unwanted because it can contaminate the steel and render it useless. Nevertheless the combination of calcium / aluminum / silica / iron compounds is less reactive than in cement. The setting of GGBS is “very” slow. The hydration of the belite takes months, years for some  $CS$ . Consequently, the mechanical strength increase is slower than for cement. The main advantage of this slow hydraulic activity in the formation of  $CAS$  is the low reactivity to sulfide or chloride salt.

The mineral composition of GGBS can vary dramatically. For this reason, it can be very difficult to find this composition (% of  $C_2AS$ ...), except for the % of  $CaO$ ,  $SiO_2$ ...

Also, the metal and / or metal oxide compound content depends on the ore composition but there is a possibility of heavy metal or carcinogenic chromium VI or vanadium presence in the slag.

GGBS also contain in bigger quantity non-suitable salt for the construction such as sulfur. The common explanation given for the blue/green coloration of some GGBS fresh mortars is the presence of  $FeS$  (iron sulfur) and  $MnS$  (Manganese sulfur). When the mortar dries, the pigmentation disappears because the sulfur oxidizes with air contact and produces  $FeSO_4$  and  $MnSO_4$  (considered as dangerous for the environment). However, some scientists explain this color by the presence of copper, cobalt and chromium salt.

The use of GGBS as a binder is a modern practice. Its first attested use in Europe is after 1870 and 1900 in the United States, in order to make slag cement for low permeability / high durability concrete.

The idea to mix GGBS with lime to produce render or plaster is very recent and its use on preservation of restoration work can be very risky:

- The GGBS' ability to minimize porosity reduces breathability at the same time.
- The slow increase in mechanical performance can lead the mortar manufacturer to underestimate the performances, if they only take into consideration (as it is usually made in the mortar industry) the 28 days results. The 90 days or 6 months results will be 2 to 5 times stronger.
- The lower speed of hydration of a GGBS mortar can also create a problem on the job site as the binder can dry before the full hydration of the GGBS. The use of a GGBS mortar is more sensitive to good practice than the weakest NHL.

The main problem is, that with standard curing conditions, manufacturers commonly underestimate this risk:

- As cubic prism or 4x4x16, allows enough water for the initial set but the dry curing chamber prohibits most of the hydration of C/S/A.

Consequently, on the lab report, we find a good porosity with "normal" strength but, on the job site, you have the worst product.

Furthermore, the sulfur, after carbonation, oxidizes into sulfate, meaning the introduction of gypsum in the mortar, contaminating other parts of the construction (the sulfur content, depending of the iron ore, can be more than 5%).

Also, due to the "unpredictable" mineralogy of the slag, the presence of  $C_3S$  can be attributed to the nature of the slag as well as the presence of cement, allowing a manufacturer using cement in his mix to conceal its use.

The purpose of adding GGBS to hydrated limes is to improve the performance of a lime which, otherwise, would not be suitable for external work, trying to obtain an artificial Hydraulic Lime mimicking the NHL. As demonstrated in this paper, the addition of  $C_xS$  and  $C_xAS$  to hydroxide does not recreate an NHL, neither by its composition nor its performance.