Durmientes de vías de ferrocarril hechos de hormigón de ceniza volante activadas con álcalis

Railway sleepers made of alkali activated fly ash concrete

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Resumen

Actualmente se estima que las vías de ferrocarril a nivel mundial contienen aproximadamente tres billones de durmientes, de los cuales 400 millones son de hormigón. Conjuntamente, sobre el 50% de la demanda mundial por durmientes (estimada en 20 millones anualmente) fue por durmientes de hormigón; además, entre el 2% y 5% de los durmientes de hormigón son utilizados en reemplazar elementos dañados. La durabilidad del hormigón, sin embargo, depende de muchos factores. En este contexto se debe hacer notar que el proceso de prefabricación de elementos de hormigón industrial en planta difiere de la fabricación in-situ, lo que les da a los primeros características que los hacen destacar en términos de durabilidad. En general, se sabe que el proceso de activación de cenizas volantes permite obtener un material con características cementantes similares a aquellas del cemento Pórtland. En realidad, las cenizas volantes activadas con álcalis es un procedimiento singular en el cual el residuo resultante de la combustión de carbón en plantas termoeléctricas es mezclado con disoluciones alcalinas que curadas bajo ciertas temperaturas generan materiales resistentes. A diferencia del hormigón tradicional, este nuevo tipo de hormigón puede alcanzar altas resistencias en un periodo muy corto de tiempo (1 día) además de desarrollar una durabilidad excelente.

Palabras Clave: Ceniza volante, activación alcalina, nuevo hormigón, durmientes

Abstract

Nowadays, the tracks that comprise the world railway network are estimated to contain nearly three billion sleepers, over 400 million of which are made of concrete. At the same time, over 50% of the world demand for sleepers (around 20 million units per year) was for the concrete version; and between 2% and 5% of the concrete ties that are laid on tracks every year are to replace or renew worn elements. Concrete durability, however, depends on many factors. And in this context it should be noted that the characteristics of the in-plant industrial process involved in manufacturing precast concrete units differs in a number of ways from in situ construction, vesting these units with properties that distinguish them, in terms of durability, from in situ concrete under the conditions generally prevailing on construction sites. Generally speaking, it is widely admitted that the activation process of fly ashes allows obtaining a material with similar cementing features to those characterising Ordinary Portland Cement. Actually, the alkali activation of fly ashes is a singular procedure by which the powder originated in the power plants is mixed with certain alkaline dissolution and cured under a certain temperature to make solid materials. Contrary to conventional concrete, however, this new type of concrete can attain high strength over a very short time (1 day) and do develop excellent durability properties.

Keywords: Fly ash, alkaline activation, new concrete, sleepers

1. Sleepers with pre-tensioned reinforcement made using the long line process

The monobloc sleeper for railway tracks is a small sized pre-stressed concrete element (it can come under the term "lightweight precast") but it is of significant economic importance in overall railway infrastructure because of its vast use.

Although it is a small item, it is not necessarily a simple one because it is subject to extraordinarily small dimensional tolerance demands and it is exposed to extremely harsh atmospheric conditions (damp - dry reversals, high temperatures in summer, winter frosts, etc.) and to important stress under very heavy vehicle loading, with frequent dynamic action that can cause fatigue problems.

Getting this product manufactured with all the determining terms of reference and at minimum cost turns it into a complicated element, in spite of its size, but this can be accomplished with more or less success by using different procedures:

- post-stressed sleepers
- pre-stressed sleepers in individual moulds
- pre-stressed sleepers with pre-tensioned reinforcement, using the "long line process"

Long line process installation at the factory consists of a series of multiple moulds placed one after the other thus forming one line or long casting bed (~100m approximately). Tensing elements and transitory reinforcement anchors are placed at the ends of this bed (see Figure 1).

Active reinforcement is placed along the casting bed and tensed at the ends prior to concreting. When the concrete is sufficiently resistant, the reinforcement anchors are slowly and gradually released so that pre-stressed force is introduced into the sleepers where the reinforcement is still anchored by adherence.

There is no cladding, no conduits around the reinforcement, no special anchor pieces, no slurry injection. Reinforcement is made from taut, straight cords perfectly adhered to the concrete. In more sophisticated long line systems, before releasing the reinforcement anchor at the ends of the casting bed, the whole line is demoulded by lowering the mould with the aid of a hydraulic system.

Figure 1. Sleepers factory. Long line process

Sleepers made by using this process and installed for seven years on tracks belonging to the Spanish railway network offer a series of specific advantages, including:

- They ensure better final track geometry (essential for high speed)
- They are more resistant to lateral stress on track.
- They provide very important allowances that could be required in advance in compliance with static, fatigue and dynamic testing.
- They guarantee uniform behaviour and similar useful life on track due to the simultaneous manufacture of a large number of sleepers.

1.1 Uniform distribution of tendons. Tension by introducing pre-stress

It is known that tensile tension appears in areas where pre-stress is introduced and that this is caused by the deflection of the compressive static stressing (isostatics) from a series of located loads concentrated at one extreme, up to a flat distribution of tension, at a distance that depends on the loads and the transverse size of the unit. The control and limitation of these tractions is vitally important since they can create longitudinal fissures that evidently might adversely affect the operability and durability of the piece. In the case of sleepers with pre-tensioned reinforcement the problem is significantly minimized, thanks to two circumstances:

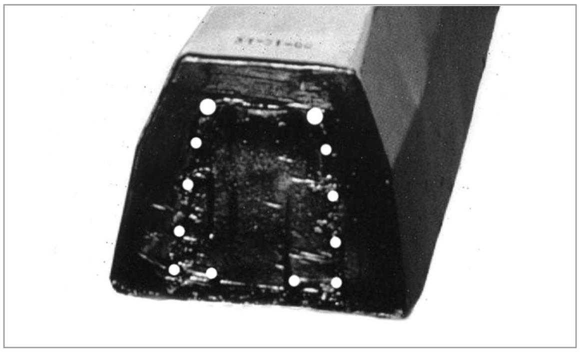

Figure 2. End of a sleeper

a) The design foresees a very uniform distribution of a large number of tendons that each has reduced strength (around 12 units) (see Figure 2).
b) The anchor is not materially concentrated at the end in a plate (mechanical type anchor) but by gradual transmission along the transfer length.

Uniform distribution and gradual transmission of the pre-stress produce a very slight deflection on the isostatics and therefore the amount of traction is kept to limited values, very distant from the tensile strength of concrete, therefore any danger of fissuring is completely avoided.

1.2 Fissure control under exceptional loads

The high adherence of pre-tensioned reinforcement required for the introduction of pre-stress over a short distance and anchored to active reinforcement *provides an important additional effect in the control, not only in the opening of fissures under exceptional loads but also in the width of the remaining fissures.*

This advantage occurs in sleepers when they are exposed to exceptional, unforeseen stress, in accidental cases (derailments) that cause impact or temporary increases that are higher than usual.

Controlled opening of the fissure is produced (when applying loads greater than those at the time of fissuring), due to the adherence fixing the reinforcement to absorb increased traction of the reinforcement inside the fissure related to the reinforcement inside the non-fissured concrete. The lesser the length over which this anchor is made, the greater the adherence, and therefore the opening of the fissure and the deformability of the sleeper are less when subjected to loading.

1.3 Geometric evidence

The concrete of a sleeper sets in the mould where it suffers a curing process until the concrete reaches very important strength (over 45 Mpa in testing cube).

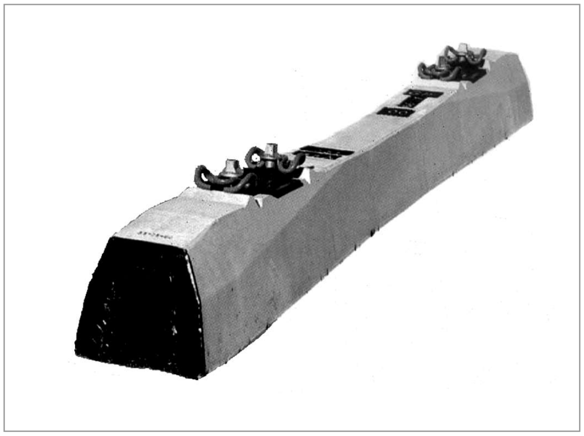

Figure 3. Final geometry of a sleeper

This process guarantees the final geometry of a sleeper as long as the mould has the correct geometry since both coincide at the time of demoulding. As demoulding takes place at a very early stage, a concrete that is still deformable could risk significant deformation and geometric alteration (see Figure 3).

True sizes of finished sleepers, both in-plant and on track, confirm geometric accuracy with much lower tolerances than those allowed under current regulations. One of the fundamental consequences in the procedure is the precision and regularity in the rail fastening area. It is decisive in the final track geometry. This aspect is extremely important at high speed.

2. Materials

Once the design has been adjusted according to the expected stress, the key factor in the manufacture of sleepers with pre-tensioned reinforcement from a structural - resistant point of view lies in obtaining the complete anchoring of the active cords over a very short distance, between the end of the piece and the section underneath the rail. This is where maximum positive bending momentum takes place. This requires excellent adherence between the reinforcement and the concrete.

Of course this adherence depends on the characteristics of the two materials involved: concrete and steel. For the active reinforcement it is advisable to use cords with 3 x 1/4"ϕ wire and 7 x 3/8"ϕ wires that provide a high surface / section ratio, and surface characteristics that provide improved adherence due to their accuracy and geometry.

As for the concrete, adherence characteristics are directly related to its compressive strength and flexure strength.

With regard to section resistance, high concrete compressive strength is not required to support calculation bending momentum. However we need to be able to anchor steel to very young concrete: during manufacture, before transferring the pre-stress, that is to say, approximately 12 hours after concreting. In short, high strength concrete is needed in the short term:
> 50 Mpa in 12 hours, thermally treated at a moderate temperature: <50º. At 28 days this concrete has a strength of between 80 and 90 Mpa and although it does not have to resist the stress, it is highly compacted which means high durability, at the same time it provides a very high margin against cracking thanks to its flexure strength.

3. Concrete without portland cement

Currently worldwide research is being carried out in order to obtain and use of conglomerate other than Portland cement that could become a future alternative (Palomo et al., 1999). Portland cement is an excellent basis for manufacturing concrete, however two reasons limit its use in future: energy consumption for manufacturing the cement and its collaboration in degrading the environmental. The Portland cement industry ranks third in the sector (after aluminium and steel) for the cost of power. Regarding gas emissions into the atmosphere, we can say that the production of one ton of cement generates approximately one ton of CO_2. Recent data from the IEA (International Energy Authority) holds the cement industry responsible for emitting between 6% and 7% of all the CO_2 emissions into the atmosphere.

To relieve this problem, studies are being carried out on the possible use of natural products and primary industry by-products (puzzolans, slag, fly ashes, clays, silica fume, etc.) to substitute cement consumption.

In this context the alkali activation of aluminosilicate materials should be considered as an interesting alternative to produce new cementitious materials. Alkali activation is a chemical process that allows the transformation of certain structures, partial or totally amorphous/vitreous/metaestable, in compact cementitious skeletons (Glukhousky et al., 1980; Krivenco et al., 1994; Palomo et al., 1999; [a]Fernández-Jiménez et al., 2003; Duxon et al., 2007).

Type F fly ashes are probably one of the aluminosilicates having better potential for use in the building industry since extraordinary high volume are produced (in 2000 over 600 million tons were produced worldwide) which in turn guarantees the supply needed in this type of industries.

3.1 Chemical composition and reaction process

The chemical composition of two commercial cements and three Spanish fly ashes is given in Table 1. The data in the table clearly shows how fly ash basically comprises silica and alumina ([a]Fernández-Jiménez et al., 2003) whereas the essential components of Portland cement are lime and silica.

Table 1. Chemical composition of cement and fly ash

	F.A. L	F.A. R	F.A. C	Cem. 42.5	Cem. 52.5
PF	1.80	0.75	3.59	3.48	1.48
RI	0.40	0.12	0.32	1.65	0.55
SiO_2	51.51	42.03	53.09	18.4	19.92
Al_2O_3	27.47	26.70	24.80	5.96	6.44
Fe_2O_3	7.23	14.42	8.01	2.17	1.16
CaO	4.39	9.60	2.44	62.83	63.28
MgO	1.86	1.87	1.94	1.43	0.63
SO_3	0.15	0.86	0.23	3.50	1.09
K_2O	3.46	2.44	3.78	0.54	-
Na_2O	0.70	0.34	0.73	0.2	-
Total	99.01	99.13	99	100.16	100

The fly ash activation process is very different from that of Portland cement hydration: In the hydration process of Portland cement a calcium silicate hydrate type gel (C-S-H) is obtained as a majority product and is responsible for the binding properties of the material (Taylor, 1997). This gel is made up of linear chains of silica tetrahedrons joined to a central sheet of CaO. However in the alkali activation process of fly ash, the end product is an alkaline hydrated silicoaluminate ([a]Palomo et al., 2004; [a,b]Fernández-Jiménez et al., 2005); this is a zeolitic precursor with a three-dimensional structure and therefore far more polymerized than the C-S-H gel.

No formation of portlandite or ettringite products of a calcium nature responsible for any durability problems associated with concrete using Portland cement are detected in the alkali activation of fly ash.

3.2 Physical appearance

Physically speaking, Portland cement mortars and concrete and activated fly ash mortars and concretes do not present great apparent differences not only in a hardened nor fresh state, as can be observed in Figure 4. However certain basic variations do exist with respect to dosing in both mortars and concrete. Mortars and concrete in new materials for example have a higher dosing of fly ash. ([b,c]Fernández-Jiménez et al., 2003).

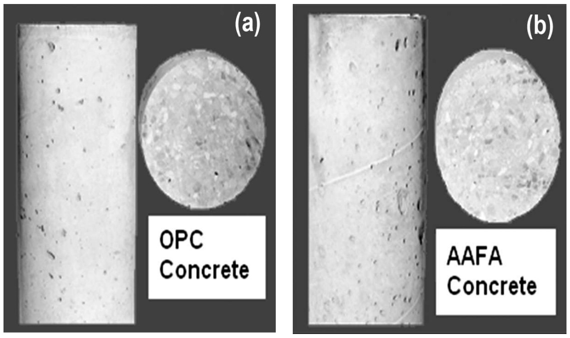

Figure 4. (a) OPC concrete (b) Activated fly ash

3.3. Mechanical properties

Some laboratory test programmes have sometimes achieved a compression strength of 100 Mpa in mortars cured at 110º for 12 hours. At cure temperatures below – 85º nearly 70 Mpa at 20 hours can be obtained, and the strength later increases up to 80 Mpa in 28 days ([b]Palomo et al., 2004; Fernández-Jiménez et al., 2008). Factory testing for concrete cubes (15x15x15cm) has not achieved such high but good enough for a good quality concrete. In Figure 5 compressive strength evolution can be observed when concrete is made though thermal curing (85ºC) for 20 hours and using as alkaline activator 8M NaOH solution.

The concrete was dosed to the following criteria: coarse siliceous aggregate (6-12 mm) / fine aggregate (0-5 mm river sand) ratio = 1.26; aggregate+sand / ash ratio = 4/1; ash dosage = 465 kg /m^3; solution N/ ash ratio = 0.4

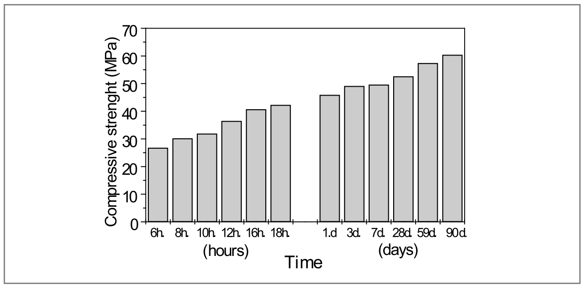

Figure 5. Mechanical strength of activated fly ash concrete

3.4 Shrinkage

Normally when a material is submitted to certain environmental conditions, it loses water and contracts. As shown in Figure 6 the alkali-activated ash mortars experience very small shrinkage on drying; clearly lower than that of cement mortars. This indicates very good volume stability, an extremely important property when designing precast items. This is especially the case with pre-stressed concrete, which benefits from very much lower pre-stress losses than usual, thanks to its practically non-existent shrinkage. (Hardjito et al., 2002; Fernández-Jiménez et al., 2006)

Portland cement mortars had a sand/binder ratio of 3/1 and a water/cement ratio of 0.5. Two sets of curing conditions were used: (a) 20h at 22ºC, laboratory standard curing conditions and (b) 20h at 45ºC, hot weather curing conditions. The sand/binder ratio used in the fly ash mortars were 2/1 and the alkaline solution (8M NaOH) /ash ratio was 0.4. These mortars were cured for 20h at 85ºC and 98% relative humidity, usual curing conditions for this type of material. After curing, the 2.5x2.5x23-cm specimens were stored in the laboratory at 21ºC and approximately 50% relative humidity.

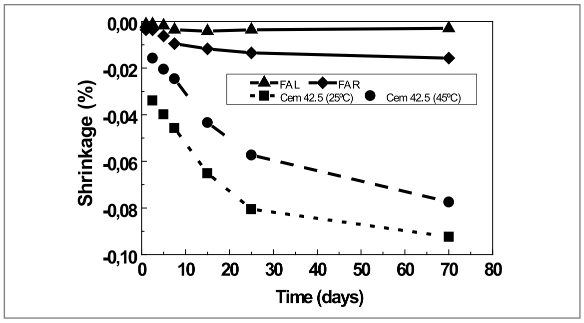

Figure 6. Shrinkage on drying in cement and alkali-activated fly ash mortars (Test conducted on 2.5x2.5x23-cm mortar specimens. (ASTM C 806-87)

3.5 Durability

It is a well-known fact that concrete is a material that must guarantee the mechanical performance foreseen in the site project where it will be used, as from the desired age, and must be maintained throughout its useful life in the expected environmental conditions. In the case of precast materials subjected to thermal curing (Butt et al., 1968), some specific problems of durability are related to the delayed formation of ettringite (Heing et al., 1987), or to the aggregate-alkali reaction (Davies et al., 1988). Regarding the durability of fly ash mortars and concrete, very limited information is readily available due to the novelty of these materials. However, we give below a summary of the behaviour expected from these new materials in view of the main problems of durability involved with Portland cement.

- Stability in acid environments. The main product that is formed in the alkali activation of fly ash is a zeolitic precuror, a sodium silicoaluminate that is more acid than C-S-H gel. Therefore its stability is greater in highly aggressive acid environments (Fernández-Jiménez et al., 2007).
- Attack by sulphates. With regard to the internal attack by sulphates suffered by thermally cured cement and even external attacks by sulphates, there are no calcium aluminates in these materials and therefore ettringite is never going to be formed (Fernández-Jiménez et al., 2007).
- Carbonatation. The main problem from the carbonatation of cement is the formation of calcium carbonate, due to the reaction of CO_2 with the portlandita Ca^{2+} ions. The pH of the porous dissolution is reduced which gives rise to the despassivation and later corrosion of the reinforcement. In the case of cement and alkali-activated ash concrete (low calcium content), highly soluble sodium carbonate can form that in principle could maintain the high pH level at the watery phase and therefore anticipate prevent corrosion of the reinforcement (Miranda et al., 2005).
- Silica - alkali reaction. The silica - alkali reaction in cement is produced basically because of the reaction between the alkali ions in Portland cement or other sources with the active siliceous components of some aggregates. Calcium-sodium silicate forms as a result of the reaction and its expansive character depends largely on the CaO content. Alkali-activated fly ash cement has a very high alkali (Na) content but this is very low in Ca. This means that the silica - alkali reaction, if it takes place, will have a much less expansive character than what is normally produced in normal cement (García-Lodeiro et al., 2007).

4. Conclusions

- Important advances in the search of new applications for the fly ashes are being achieved: The development of a new type of binder alkali activated fly ash (AAFA) is a good example of it.
- Results have proved that these new AAFA concretes develop good mechanical strength in a relatively shorts period of time and very low dry shrinkage.
- Another aspect deserving special attention is the possibility to obtain different qualities of concrete by

modifying the nature of the alkaline activator used.

- *Finally these results show the potential for use of such materials in the near future in construction it is very important to draw attention on the easy way this material adapt itself to the installations already existing in current precast industry.*

5. Further Research

The scientific community has made considerable efforts in recent years to find new binders suitable for use in construction that would enhance the properties of the traditional binder while costing much less than Portland cement to manufacture, in terms of environmental impact and energy consumed. Alkaline cements obtained from the alkali activation of fly ash (AAFA) are among the materials with greatest potential to provide a feasible alternative. The study of certain engineering properties of new Portland cement-free alkaline concretes made with AAFA can be the next objected, properties as: wetting-drying test, freezing-thawing test, behaviour at high temperature, etc.

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