Structural behaviour of prestressed concrete sleepers produced with High Performance Recycled Aggregate Concrete

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Abstract

A comparative analysis of the structural behaviour of prestressed concrete sleepers made with High Performance Concrete (HPC) and High Performance Recycled Aggregate Concrete (HPRAC) is presented in this study. Two types of HPRAC sleepers were tested, using 50 and 100% of Recycled Concrete Aggregate (RCA) in replacement of the coarse natural aggregates. The RCA sourced from crushing old rejected of HPC sleepers. The aim of this study was assessing the HPRAC sleepers' behaviour according to the minimum requirements defined by European standards for prestressed concrete sleepers and compare their experimental behaviour with that of the HPC sleepers. The three types of prestressed concrete sleepers were subjected to static load tests at rail-seat and centre section (positive and negative load). In centre section tests, a comparison between the experimental results and the proposed values from four assessment methods of ultimate capacity was carried out. Also dynamic load and fatigue tests were performed at the rail-seat section. According to experimental results, the HPRAC-50 and the HPRAC-100 had a satisfactory performance, and very similar to that of the conventional HPC sleepers. The load-strain behaviour recorded via the use of strain gauges at the prestressing bars revealed slightly higher stiffness on the HPC sleepers. The values found from the four assessment methods of ultimate capacity were also accurate when applied to HPRAC. The structural requirements for prestressed concrete sleepers were extensively verified by the sleepers made with HPRACs, except, as HPC sleepers, in the static negative load test at centre section.

1. Introduction

According to European Union statistics from 2012 onwards [1], construction has become the industrial sector producing the highest amounts of waste. For the last twenty years, the awareness of governments and public institutions of the importance of recycling Construction and Demolition Waste (C&DW) has increased. In spite of developing new standards and directive frameworks to reduce the C&DW disposal in landfills, the recycling ratios are still insufficient, especially in southern European countries. The on-site recycling of demolition materials is the most efficient process of reducing waste landfill and natural aggregates consumption, as well as reducing transportation costs and detrimental environmental impact.

Several types of recycled aggregates can be obtained from C&DW. Recycled Concrete Aggregates (RCA) has been reported as the recycled aggregate type with the most suitable physical and mechanical properties. The predominant composition of concrete particles in RCA prevents the higher sulphate contents and lower densities which are normally caused by the presence of gypsum and masonry particles. Nonetheless, most properties of the RCA are usually poorer than those of natural aggregates, especially the properties of water absorption, porosity and crushing value due to the old mortar attached to the aggregates [2, 3].

Over the last twenty years, there have been many studies which have concerned themselves with the influence of RCA on the physical, mechanical and durability properties of Recycled Aggregate Concrete (RCA) [4–15]. Comparative studies of the RCA with natural aggregates conclude that the lower properties of the RCA have in general negative effects on the properties of the Recycled Aggregate Concrete (RAC). Some typical negative effects are, lower workability due to their higher water absorption, lower compressive strength and lower durability properties due to RCA’s lower mechanical toughness and higher porosity. Nevertheless, RCA can be successfully used in the production of low and medium strength concretes if the recommendations on the maximum replacement ratios, minimum qualities, specific mixing methods or mix designs using mineral admixtures are implemented [2, 10, 14, 16–20].

Currently, few studies have dealt with the use of RCA in High Performance Concrete (HPC) [21–25]. In particular Ajdukiewicz and Kliszczewicz [21], Kou and Poon [23] and our previous studies, Gonzalez-Corominas and Etxeberria [26], were focused on the use of coarse RCA, sourced from the waste of HPC and high quality concrete, in the production of new High Performance Recycled Aggregate Concrete

(HPRAC). These studies agreed that the mechanical and durability properties of HPRAC produced with high quality RCA could achieve higher mechanical and durability properties than those of conventional HPC, even when using high replacement ratios (50-100%) without any cement adjustment.

High Performance Concretes are produced to achieve higher compressive strength and higher durability properties than conventional concrete while at the same time maintaining proper workability [27]. These properties are particularly suitable for their application in prestressed concrete elements such as prestressed concrete sleepers. Mono-block prestressed concrete sleepers, which were first employed in the early 40’s, have become essential components in high speed rail track constructions worldwide [28, 29]. The extraordinary development of high speed train networks in Europe and Asia [30], has led to a great number of studies on the production of prestressed concrete sleepers in order to develop safer railway structures, which could hold higher loading demands [31].

Several studies have concerned themselves with the structural performance of concrete sleepers, focusing on crack development, fatigue and impact behaviour [32–39]. Other principal concerns have been the durability properties and their service life [38, 40, 41]. However, very few studies have considered the production of environmentally sustainable sleepers [31, 42–45]. These eco-friendly prestressed concrete sleepers have been developed by partially replacing Portland cement for ground granulated blast furnace slag and replacing natural fine aggregate by electric arc furnace oxidizing slag. The results obtained from the analysis of the eco-friendly prestressed concrete sleepers showed an improvement on those obtained from conventional prestressed concrete sleepers.

In this research work, the influence of HPRAC on the structural properties of prestressed concrete sleepers was analysed. The RCA used in the HPRAC sourced from old rejected sleepers and the replacement ratios of natural coarse aggregates were 50 and 100%. Conventional HPC sleepers and HPRAC sleepers underwent static and dynamic load tests at the centre and rail-seat sections as defined in European standards and Spanish specifications for prestressed concrete sleepers [46, 47]. The load-stress behaviours of the prestressing bars were recorded using strain gauges in order to carry out a comparative study of the structural performance of the HPRAC sleepers.

2. Experimental details

2.1. Materials

2.1.1. Cement and admixture

In the production of the HPC, a rapid-hardening Portland cement (CEM I 52.5R) with low alkali content was used. Their specific surface and density were 495 m^2/kg and 3150 kg/m^3, respectively. According to the regulations laid down in the Spanish railway specifications [47], the Portland cement was found to have low alkali content. This rapid-hardening cement was employed in order to achieve high-early strength for the prestressing bars release after 24 hours of curing. The admixture used in the HPC production was a high performance superplasticizer based on modified polycarboxylate-ether with a specific gravity of 1.08.

2.1.2. Aggregates

The natural aggregates were those already used in the production of HPC for commercially-available prestressed sleepers from a Spanish precast concrete company. The natural fine aggregates were two river sands mainly composed of silicates with two different particle size fractions (0-2mm and 0-4mm) in order to achieve higher compaction. Two types of coarse natural aggregates were used, rounded river gravel (siliceous) and crushed dolomite, to improve the workability and the mechanical behaviour of the concrete. The RCA used in replacement of both natural gravels was sourced from crushing old rejected sleepers, whose characteristic compressive strength after 28 days was 100 MPa. The concrete waste was crushed and sieved to achieve RCA with similar particle size distributions to those of the coarse natural aggregates. The physical properties of the natural and recycled aggregates are shown in Table 1.

The coarse natural aggregates had higher density and lower water-absorption than the recycled concrete aggregate, a fact also reported in several studies [2, 3, 48]. However, the physical and mechanical properties of the RCA, which are directly related to the strength of the parent concrete [49, 50], were more similar to NA than those found in other studies [8, 49, 51] due to the high quality of the parent concrete.

2.2. Concrete mixtures

All concrete mixtures were produced in a Spanish precast concrete plant. The proportioning of the natural aggregate concrete was that already used in HPC for the production of prestressed concrete sleepers according to the Fuller's dosage method [52]. As shown in the concretes proportioning from Table 2, 380 kg of cement and a total water-cement ratio of 0.35 were used in the HPC production. For the production of HPRAC, the natural coarse aggregates were replaced by 50 and 100% of RCA (in volume). The cement amount and the effective water-cement ratio were kept constant in the HPC and the HPRACs production (considering effective water as that amount water reacting with the binder or not stored in the aggregates [53]).

The admixture were used in 1% of the cement weight in order to maintain dry consistencies, 0-20 mm in the concrete slump test (UNE-EN 12350-2:2009). The natural fine aggregates were used in saturated conditions and the recycled coarse aggregates at 80-90% of saturation at the moment of concrete production.

2.3. Mechanical properties of HPC and HPRAC

The concretes mixtures were tested prior to sleeper production, in order to ensure that they met the requirements of the Spanish railway technical specification [47]. The compressive strength, splitting tensile strength, flexural strength and modulus of elasticity tests were carried out following the corresponding EN specifications. The results of the mechanical properties obtained as well as the minimum technical requirements according to the Spanish prestressed sleepers' specification can be observed in Table 3.

HPC and HPRAC with 50 and 100% replacement ratios fulfilled the requirements established for the mechanical properties of concrete mixtures As found in previous studies [25], RCA sourced from parent HPC of 100 MPa could be used in the production of new HPRAC in replacement ratios of up to 100% with no negative effects on the mechanical properties. The high quality of the RCA and the improvement on the Interfacial Transition Zone [8, 14] could be responsible for the enhancement of the mechanical performance of HPC using recycled aggregates.

2.4. Prototype of prestressed concrete sleeper

The prototypes of the prestressed HPRAC sleepers and the reference prestressed HPC sleepers were produced in a Spanish precast concrete plant. The manufacturing procedure, the geometrical dimensions of the sleeper, the prestressing bars and tension were kept constant for all concrete mixtures, in order to analyse the influence of HPRAC in the structural properties and later compare them with the values obtained from the reference HPC sleepers. The concrete mixtures in the sleeper's moulds were compacted in two stages of 30 seconds via the use of a vibrating table. The sleepers were stored immediately after casting in a standard curing room (23±2° and 95% of humidity) for the first 24 hours. After 24 hours, the prestressing tension of the reinforcing bars was released and the sleepers were demoulded. Fig. 1 indicates the schematics of the prestressed concrete sleeper's prototypes. Fig. 2 indicates the stress-strain behaviour of the Ø 9.5 mm prestressing bars (Y1570C) obtained from the tensile strength test.

3. Test setups

Five structural tests were carried out in accordance with the European Standards (EN 13230-2:2009) and the Spanish railway technical specification for prestressed concrete sleepers (ET 03.360.571.8:2009) [47]: 1) Static positive load test at the rail-seat section, 2 and 3) Static negative and positive load test at the centre section, respectively 4) Dynamic test at the rail-seat section, and 5) Fatigue test at the rail-seat section.

3.1. Static positive load test at the rail-seat section

The arrangement for positive bending test on the rail-seat section is shown in Fig. 3. The load Fr was applied perpendicularly to the base of the sleeper and centred in one of the rail-seat sections. The tested rail-seat section was located between 389.5 mm and 687.1 mm from the edge of the sleeper. The sleeper had only one support under the testing rail-seat section and the opposite non-tested edge was unsupported.

The procedure followed in the static test at the rail-seat section is shown in Fig. 4. The initial vertical loading force was increased up to the initial reference load (Fr_0), which in the case of 1435 mm track gauge was 156 kN according to the Spanish specification [47], with a loading rate of 60 kN / min. After the initial reference load, the loading was increased in 10 kN intervals, maintaining the load in every interval for 30 seconds up to the first crack formation. After the first crack appearance, a new series of loading and unloading intervals started, increasing 10 kN in every loading interval.

The Spanish technical specification for prestressed concrete sleepers [47] indicates that the load which produces the first crack formation (Fr_r) should be higher than the initial reference load (Fr_0). Also the load ($Fr_{0.05}$), which produces a crack of 0.05 mm width at the bottom after the removal of the load, and the ultimate load (Fr_B) should be higher than 280 kN and 390 kN, respectively.

Two traditional HPC sleepers and six HPRAC sleepers for each replacement ratio were tested for the static positive load test at the rail-seat section. Two strain gauges were placed on the two inferior prestressing bars, one per side, centred in the rail-seat section perpendicularly to the load plane in order to analyse the stress-strain behaviour.

3.2. Static load test at the centre section

3.2.1. Negative design

The arrangement for the negative load test at centre section is shown in Fig.5 (a). In order to carry out the negative bending test, the sleeper was placed upside down on the testing frame. The load Fc was applied at the centre of the sleeper and perpendicularly to its base.

The static test procedure at the centre section for negative design approval test is shown in Fig. 4. According to the Spanish specification [47], the initial reference load was 42.5 kN which were attained with a loading rate of 60 kN / min. Once the initial reference load was reached, it was maintained for 30 seconds. After that time, the load was increased in 5 kN intervals, maintaining the load in each interval for 30 seconds up to the sleeper's ultimate bending load. The load which produced the first crack formation was recorded during the test.

The criterion for the acceptance was that the load producing the first crack (Fc_r) had to be higher than the initial reference load (Fc_0), which was 42.5 kN according to the Spanish specifications [47]. Two HPC sleepers and three HPRAC sleepers for each replacement were tested in the static negative load design. Strain gauges were installed on the superior bars in the centre section to register the maximum strain under negative bending.

3.2.2. Positive design

The test arrangements for the positive centre load test were the same as those from the negative load test, except for the sleepers were placed in its ordinary position as shown in Fig. 5 (b). The test method followed the procedure described in Fig. 4 which was the same as in the negative load test but with a reference load of 30 kN. The only acceptance requirement was that the load which produced the first crack (Fc_r) had to be higher than the initial reference load (Fc_0). Two HPC sleepers and three HPRAC sleepers for each replacement were tested in the positive design,. Two strain gauges were installed on the inferior bars for each sleeper tested in order to register the maximum strain under positive bending.

3.2.3. Prediction of the ultimate capacity of the HPC and HPRAC sleepers at centre sections.

A comparison between the experimental static test results at centre section and the values obtained following different methods for the prediction of ultimate capacity of reinforced or prestressed concrete sections was carried out. Different hypothesis to contemplate the concrete behaviour at the ultimate limit state were considered with the underlying purpose to validate them when applied to recycled aggregate concretes. Therefore, it was assessed whether the methods used for the calculations of the ultimate capacity of reinforced or prestressed concretes yield reasonable values for the different replacements of coarse aggregate.

Four different stress-strain diagrams for concrete at ultimate state were considered; the bi-linear stress-strain; the quadratic parabola diagram; the parabola rectangle according to Eurocode 2 [54] and a variation of the last one according to SIA262 [55] (see Fig. 6). All the diagrams depicted in Fig. 6 represent a simplification of the concrete behaviour under ultimate states.

The ultimate strain allowed and determined by Eurocode [54] for concrete was ε_{cu}=0.0026. The ultimate strain value had a essential role in the prediction of the ultimate cross-section capacity. Different authors [56] claimed that there was no difference in the ultimate strain between conventional concrete and recycled aggregate concretes with the same compressive strength. However, they yield dissimilar behaviours in the softening branch.

The material model chosen for the prestressed bars was a bilinear model with hardening, taking the recommended hardening coefficient k=1.1 as proposed in the Eurocode 2 [54]. In this case, as it was described in the previous sections, the steel’s class was Y1570 and the maximum strain allowed before failure was ε_{uk}=20% (see Fig. 7).

3.3. Dynamic test at the rail-seat section

The test arrangement for both the dynamic and static tests at the rail-seat section were the same (see Fig. 3). The test procedure followed in the dynamic test at the rail-seat section is shown in the Fig. 8. The test is based on the application of series of 5000 loading-unloading cycles with a frequency of 5 Hz. For all series, the loading-unloading cycles started at a minimum test load (Fr_u) of 50 kN. In the initial series, the maximum test load was the initial reference test load for the rail-seat section (Fr_0), which according to the Spanish specification was 156 kN. For the following series, the maximum test load was increased 20 kN in each series. After each loading interval, a crack measurement was performed. The maximum time employed in the inspection was 5 min.

According to the Spanish specification [47], the load ($Fr_{0.05}$) which produces a crack width of 0.05 mm at the bottom after the load removal has to be higher than 1.5 times the initial reference test load (234 kN). The maximum positive test load (Fr_B) has to be higher than 2.2 times the Fr_0, which 343 kN. Two conventional HPC sleepers were tested for the dynamic bending test at rail-seat section, whereas six tests were conducted for HPRAC sleepers in each replacement ratio.

3.4. Fatigue test at the rail-seat section.

The test arrangement for the fatigue test at the rail-seat section was the same as that from the rail-seat section test shown in Fig. 3. The test procedure followed in the fatigue test at the rail-seat section is shown in Fig. 8. The sleepers were initially loaded until the appearance of the first crack. Immediately after the first crack formation, the fatigue loading cycles, which consisted of 2 million cycles of 5 Hz frequency, started. The cycles were restricted to a loading range from a minimum load (Fr_u) of 50kN to a maximum load (Fr_0, reference load) of 156 kN. Finally, the sleeper was loaded until failure with a rate of 120 kN/min to obtain the ultimate load (Fr_B) after the fatigue series.

According to the acceptance criteria from the Spanish specifications, the crack width has to be lower than 0.1 mm and 0.05 mm when loaded at Fr_0 and when unloaded, respectively. The failure load (Fr_B) after the 2 million loading cycles has to be higher than 2.5 times the initial reference load (Fr_0), which is 390 kN. For each concrete mixture, one sleeper was tested according to the requirements from the Spanish specification [47]. Two strain gauges were installed in the centre of each inferior bar in order to study the strain behaviour.

4. Results and discussion

4.1. Static positive load test at the rail-seat section

Both the conventional HPC sleepers and HPRAC sleepers fulfilled the first crack formation regulation requirements. No cracks appeared under the initial reference load (156 kN). As Table 4 shows, the load which produced the formation of the first crack (Fr_r) was very similar to that applied to all the sleepers (219-221 kN). However the results obtained by HPRAC showed a higher variability to those of HPC. In spite of showing higher standard deviations, the Fr_r value of HPRAC sleepers were sufficiently high to ensure their acceptance requirements according to the Spanish standard [47].

The average results of the $Fr_{0.05}$ load, which produced cracks of 0.05-mm width, as well as the Fr_B, failure load, of all sleepers satisfied the minimum requirements [47]. The average $Fr_{0.05}$ load value obtained by the HPRAC sleepers were 3% lower than that of the HPC sleepers for both replacement ratios. Moreover, the average failure load (Fr_B) of the HPRAC-50 and the HPRAC-100 sleepers were 5% and 3%, respectively, lower than that of the conventional HPC sleepers. However, the difference between the average values obtained by the HPC and the HPRAC sleepers were lower than those standard deviations from the HPRAC results. It is also noteworthy that the results of HPRAC were slightly higher than those of the prestressed concrete sleepers commonly used in South Korea [31, 43].

Fig. 9 shows the results given by the strain gauges installed at the centre of the rail-seat section in the inferior bars of the sleepers. The behaviour results obtained from the HPRAC sleepers were very similar to those obtained from the HPC sleepers. However the flexural stiffness of the HPC sleepers was slightly greater than that of the HPRAC sleepers.

According to Koh et al. [31], the recovery capability indicator of damaged sleepers can be measured via the subtraction $Fr_r – Fr_{0.05}$. The recovery indicator of the HPC sleepers (175 kN) was very similar to that of the HPRAC sleepers (160-165 kN). Moreover the obtained results were significantly higher than those results obtained by conventional prestressed concrete sleepers presented by Koh et al. [31]. Those results pertaining to those normally used by the Korean railway industry.

4.2. Static load test at the centre section

4.2.1. Negative design

The results obtained via the static negative load test at the centre section of all three types of concretes are indicated in Table 4. According to the results obtained, it was the most critical test for both the HPC and the HPRAC sleepers. Only the average Fc_r value of the HPRAC-50 sleepers achieved a higher value than 42.5kN, which is the minimum requirement in accordance with the Spanish specifications. In all the tested HPC and HPRAC-100 sleepers, the formation of the first crack was observed before reaching the Fr_0 value, which is the initial load reference value. Consequently, the results revealed that the use of HPRAC at any replacement ratios had no influence on the static negative load’s results.

The results obtained of conventional and eco-friendly prestressed concrete sleepers tested by Koh et al. [31, 42] were significantly higher than the values obtained in this research work. The concretes used in those studies had a characteristic compressive strength of 58-73 MPa at 28 days and the initial cracking formation loads (Fc_r) were 92 - 110 kN. Although the lower compressive strength of the sleepers tested by Koh et al. studies [31, 42] (the compressive strength of the HPC and the HPRAC mixtures was of 100-102.5 MPa, see Table 3), the Fc_r values obtained by Koh et al. were higher than those found in this study due to the use of higher amount of prestressing bars.

Overall, in our specific case, the failure of the HPC and the HPRAC-100 sleepers to comply with the Spanish regulation values was due to too low Fc_r load results. These low results could be caused by inefficient design reasons but not as results of the RCA influence.

All three sleepers described similar slopes on the elastic zone, as shown in Fig. 10. The HPC and HPRAC-100 sleepers had also very similar plastic behaviour. All concrete sleepers showed small yielding, the same load being applied for the first crack formation and very similar strain results obtained for each step of loading.

In the HPRAC-50 sleepers, the formation of the first crack was produced at higher loads than that applied on the other concrete sleepers, as previously mentioned. Moreover, since the occurrence of the first crack, the HPRAC-50 sleepers showed slightly higher yielding and higher strain values than those found in the HPC and HPRAC-100 sleepers.

4.2.2. Positive design

For all sleepers, the positive loads (Fc_r) which caused the formation of the first crack at the centre section were much higher than the initial reference load (Fc_0) (See Table 4). The results of HPC and HPRAC-100 were very similar. The average Fc_r and Fc_B load values achieved by the HPRAC-100 sleepers were only 2% and 1%, respectively, higher than those of the HPC sleepers. The HPRAC-50 sleeper achieved 5% lower Fc_r load value than that of the HPC sleepers, and the Fc_B value of the HPRAC-50 was similar to that of the HPC sleepers. In spite of the minor variations between the HPC and the HPRAC sleepers' results, their behaviour on the static positive load test was considered the same according to their standard deviations. The HPRAC sleepers' results deviation were higher than those of the HPC sleepers, nonetheless most of them represented less than 5% of variability, which ensured their wide acceptance according to the requirements given by the Spanish regulation.

Fig. 10 indicates the results of the static positive load test, which was obtained by strain gauges adhered to the inferior bars which were located at the centre section. The gauges of the HPC and HPRAC-50 sleepers showed similar elastic slopes, however the gauges of the HPRAC-50 sleepers showed lower yield point than those obtained by the HPC sleepers. The gauges of the HPRAC-100 sleepers showed lower slopes on the elastic zone, however they achieved a similar yield point to that of the HPC sleepers.

4.2.3. Prediction of the ultimate capacity of HPC and HPRAC sleepers at centre sections.

After introducing all the parameters in a specific sectional analysis software, it was possible to obtain the ultimate bending capacity values of the cross-section in both their negative and positive orientations. The output of the analysis for positive loading is described in Fig. 11.

As expected, the failure was produced due to the crushing of the concrete's specimens' compression head as detected in the experimental work. However a high ductile behaviour of the cross-section was detected just before the failure occurred, and the prestressed bars reached deformations of up to 15%. In Table 5 the ultimate moment, M_u, of the cross-section using the different methods is described. The corresponding applied load, as described previously in section 3 (test setup) is also indicated in the same table. The load was calculated by applying the expression:

$$F_u = \frac{4 \cdot M}{L} \qquad (1)$$

Where F_u corresponds to the external applied load in the 3-point bending test, L corresponds to the total span length and M to the applied moment in the mid-span cross-section due to the external load.

Table 6 shows the ratio between the ultimate load values, which were determined in accordance with the different methods of calculations applied in a cross-section capacity analysis (F_u) with respect to the measured failure load in the tests (F_{test}).

As expected the differences between the four cross-section diagrams used were minimal, however, in all cases the Quadratic parabola method was the one which adjusted better to the test data. In addition, it was observed that the prediction of the ultimate capacity was basically the same in all cases, which confirms that the hypothesis made for the ultimate strain was sufficiently accurate.

The ultimate concrete strain used in the analysis showed, in general good agreement when assessed the positive design section capacity, however it could be a bit conservative when applied to negative design, due to the higher contribution of the concrete. In any case, the value proposed in the EC2 [54] achieved good results and always in the safety side for any type of concrete.

4.3. Dynamic test at the rail-seat section

The results of the dynamic positive load test at the rail-seat section are summarized in Table 4. The HPRAC sleepers, for both replacement ratios, as well as the conventional HPC sleepers met all the requirements defined by the Spanish specifications. The load values which caused the initiation of the crack formation in the HPRAC sleepers were very similar to those values obtained from the static load test. However, the HPC sleepers achieved slightly higher values in dynamic test than in the static load test. Consequently the influence of the replacement ratio in this test can be confirmed. The Fr_r average value of the HPRAC-50 and the HPRAC-100 sleepers were 8 and 11% lower than that of the HPC sleepers, respectively.

The $Fr_{0.05}$ loads average values, which produced a crack width of 0.05 mm, of the HPRAC and the HPC sleepers were higher than the required value of 234kN (Spanish regulations). The $Fr_{0.05}$ load values of the HPRAC sleepers were the same for both RCA replacement ratio concretes and were slightly lower (1.4%) than those of the HPC sleepers. The average ultimate load values, Fr_B, of all the sleepers were higher than those designated as the minimum requirement value of 343 kN. The HPRAC sleepers with 50 and 100% RCA replacement ratios achieved 2.4 and 1.6% higher average ultimate loads, respectively than those of the HPC sleepers. The standard deviations achieved in the HPRAC sleepers were higher than those of the HPC sleepers for all the obtained load test results.

The results achieved by the HPRAC sleepers were very similar to those described by Carpio et al. [34]. In both cases the used conventional HPC sleepers had similar designs. However those sleepers were produced with prestressing bars of 7 mm (smaller diameter than in this research study), thus achieving lower load values in any dynamic test. In contrast, Koh et al. [31, 42] found higher values at the dynamic load test than those obtained by the HPRAC sleepers, however, the difference between these values was smaller than that observed in the static load tests.

According to Koh et al. [31], when compared to static tests, there are certain factors that influence the lowering of strength in dynamic tests. Those factors being: pronounced micro-cracks, weakened bonding strength due to delamination and severe loading conditions. As a result of this phenomenon the minimum requirements for dynamic tests are moderated in most of the international standards. The required load values for the dynamic tests are 16 and 12% lower than those required for the static test according to the Spanish specification. The conventional HPC sleepers achieved 10.9 and 17.6% lower $Fr_{0.05}$ and Fr_{B} values in the dynamic test than those in the static test. However, the dynamic results obtained by the HPRAC sleepers were only 9.4-9.8% and 9.6-11.1% lower than the static $Fr_{0.05}$ and Fr_{B}, respectively. Therefore, the HPRAC sleepers showed superior dynamic behaviours than those of HPC or those considered as the minimum requirements.

4.4. Fatigue test at the rail-seat section.

The fatigue test results, at the rail-seat section, are summarized in Table 4. Firstly, a positive load was applied at the rail-seat section until an initial crack was formed (cracking load, Fr_{r}) and later 2-million-cycle fatigue load was applied. After the fatigue cycles were applied, the width of the crack was measured in loaded and unloaded conditions. According to the Spanish specification, the crack widths shall not be wider than 0.1 mm and 0.05 mm in loaded and unloaded conditions, respectively. HPC and HPRAC sleepers reported minor cracks which fulfilled both requirements. After the crack measurements, the sleepers were subjected to increased loads until their failure. All the maximum loads of the HPRAC sleepers as well as the HPC sleepers met the minimum requirements of load failure of 390 kN. The HPRAC-50 sleeper achieved the highest failure load and the HPRAC-100 sleeper the lowest. Nonetheless, the HPRAC sleepers' results only varied less than ±5% in comparison to the HPC sleeper's results.

Carpio et al [34] verified that the use of larger diameter prestressing reinforcements and corrugated rebars instead of smooth bars had a beneficial influence on the ultimate fatigue load. Nevertheless, the HPRAC sleepers achieved higher fatigue load values than those obtained by conventional prestressed concrete sleepers according to other researchers [31, 42]. The sleepers tested by them employed a significantly higher amount of reinforcement than that employed in the HPRAC sleepers. In addition, the HPRAC sleepers also achieved similar or higher fatigue load results to those values described by Carpio et al. [34] which used corrugated rebars. Therefore, the high strength of the HPRAC concrete permitted a reduction in the amount of reinforcement while still keeping an adequate dynamic performance.

During the 2 million cycles of the fatigue load test, the strain values were obtained and registered via the use of strain gauges located on the inferior bars at the rail-seat section. Fig. 12 shows the relationship between the strain and loading cycles when the sleepers were both loaded with the initial reference load

Fr_0 and also the lower load Fr_u. The strain values obtained via the strain gauges were very similar for the HPRAC and HPC sleepers. At first, the strain values of the HPC sleepers were slightly lower than those obtained from the HPRAC sleepers. However, the HPC sleepers showed higher strain increase during the first 400,000 cycles than the HPRAC sleepers. In the following cycles, all three types of sleepers showed similar strains until the test ending. In the following cycles, the strain of the HPC and the HPRAC sleepers achieved stable values of between 120 and 150 με, thus showing similar results between the different sleeper types. Overall, it can be concluded that the fatigue behaviour of the HPRACs sleepers was similar to that of the common HPC sleepers.

5. Conclusions

After the analysis of the structural behaviour of conventional High Performance Concrete and the High Performance Recycled Aggregates Concrete sleepers under the common static and dynamic tests defined by most international standards, the main conclusions drawn from the study are:

According to static positive load:

- The crack formation as well as failure load of the HPRAC sleepers was slightly lower than the HPC sleepers when the load was applied on rail- seat section. However the HPRAC and the HPC sleepers achieved similar cracking as well as failure load when the load was applied at centre section.

According to static negative load:

- The cracking load was inferior to minimum requirements independety the material used in sleeper production. Only the HPRAC sleepers with 50% of RCA achieved the minimum requirements.

The simplified methods to predict the ultimate capacity of HPC achieved reasonable values when they were applied to HPRAC. The ultimate concrete strain used in the analysis could be a bit conservative when applied to negative design due to higher concrete contribution. However, the value proposed in the EC2 achieved good results and always in the safety side for any type of concrete.

According to dynamic load:

- Although the cracking loads of the different HPRAC sleepers were lower than that of the HPC sleepers the ultimate load of the HPRAC sleepers was higher than that of the HPC sleepers a at rail-seat section. The load-strain results from fatigue test revealed lower strain from HPC sleepers at the initial cycles. However after that initial cycles' period, HPC and HPRAC sleepers showed the same strain behaviour until the test ending

In general the HPRAC sleepers' values presented a higher standard deviation and their load-strain ratio was slightly lower than that of HPC. However, all structural requirements for prestressed concrete sleepers were extensively verified by sleepers made with HPC and HPRAC, except from the static negative load test at centre section. The HPRAC mixtures which contained 50 and 100% high quality recycled concrete aggregates sourced from parent HPC concretes showed very similar structural properties to those from conventional HPC. The concrete waste from rejected sleepers can be reused as RCA replacing up to 100% of the natural aggregates in prestressed concrete sleepers with no significant influence on the structural behaviour.

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