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Abstract: This research conducts a full-scale study on the use of recycled mixed aggregates from construction and demolition waste and its screening waste in an experimental bike lane. The subgrade and the natural and recycled materials used as the base and subbase courses were characterized in a laboratory. During the construction of the experimental section, densities and deflections were measured to evaluate the mechanical behaviour of the structural layers and to determine the Young's modulus of the natural and recycled materials. After the lane was open to traffic for two years, the moduli evolution of the materials were studied. For the first time, the results obtained have shown the feasibility of using screening waste that does not meet the physical-mechanical and chemical requirements for use on paved roads as structural layers in bike lanes.

Highlights

- An experimental bike lane was constructed with low quality recycled aggregates.
- Screening wastes from construction demolition wastes were used as structural layers.
- Young's moduli of recycled materials placed on site have been calculated.
- New limits for sulphate content, organic matter, soluble salts, Los Angeles abrasion were proposed.

Recycling screening waste and recycled mixed aggregates from construction and demolition waste in paved bike lanes

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Abstract

This research conducts a full-scale study on the use of recycled mixed aggregates from construction and demolition waste and its screening waste in an experimental bike lane. The subgrade and the natural and recycled materials used as the base and subbase courses were characterized in a laboratory. During the construction of the experimental section, densities and deflections were measured to evaluate the mechanical behaviour of the structural layers and to determine the Young's modulus of the natural and recycled materials. After the lane was open to traffic for two years, the moduli evolution of the materials were studied. For the first time, the results obtained have shown the feasibility of using screening waste that does not meet the physical-mechanical and chemical requirements for use on paved roads as structural layers in bike lanes.

Keywords:

Bike lane, backcalculation, recycled mixed aggregates, screening waste, construction and demolition waste.

Acronyms:

AASHTO - American Association of State Highway and Transportation Officials; CBR – California Bearing Ratio; CDW - construction and demolition waste; CRA - Catalogue of pavements with Recycled Aggregates; CS-1 – Crushed Limestone; EBL – Experimental Bike Lane; FWD – falling weight deflectometer; NA – Natural aggregates; PG-3 – Spanish general technical specification for road construction; RA - recycled aggregates; RCA – Recycled concrete aggregates; RMA – recycled mixed aggregates; RMSW - Recycled mixed aggregates with screening wastes; RMCA – Recycled Mixed Ceramic Aggregates; SG-1 – Subgrade; SS-1 – Selected Soil; SW – Screenings wastes.

1 Introduction

Quarries in Europe produced a total of 1000 million tons per year of stone in 2010 [1]. In Spain, the total amount of natural aggregates (NA) produced in 2012 was 208 million tons [2]. An alternative to NA could be the use of recycled aggregates (RA) from construction and demolition waste (CDW). In 2012, CDW production was roughly 821 million tons in the European Union, and in Spain alone, the amount was 20 million tons in 2014 [3]. The amount of waste from the construction industry used as filling material or illegally dumped on empty lots has been increasing over time [4]. CDW is mainly composed of 80% inert materials such as concrete, ceramics, tiles and bricks [5], which have high recycling potential.

Recycling plants can be stationary or mobile, and a mobile plant typically consists of a crusher as well as sorting and sieving devices. The quality of RA obtained in these plants is lower than in stationary plants where several crushers work in conjunction with sieving devices [6].

A “good practice guide” regarding the production and utilization of CDW was recently in published Andalusia, Spain [7]. Public administration, waste management companies and other agents involved in RA production needed a document that explained the technical and legal matters of this recycling process.

In 2015, Spanish recycling plants generated 1.6 million tons of screenings waste (SW), which were sent to landfills [8], which caused clogging and wasted a material that could be recycled. At present, no other use is provided for these materials because SW does not meet road specifications to be used as a filler or in other structural layers. High sulphate, soluble salts and gypsum contents are among the reasons why SW cannot be used as road structural layers [9]. High content of impurities in the fine fraction is typically expected in RA, as well [9]. Lack of landfill areas and the high environmental impact of mining natural aggregates increases the need to conduct experimental studies on SW recycling. Finding viable alternatives for the use of SW favours the development of environmentally friendly construction.

To promote the use of recycled materials from CDW, a catalogue of pavement made with recycled aggregates (CRA) [10] was issued on 2017. This catalogue is a pre-normative draft published by the Public Works Agency of the Regional Government of Andalusia (Spain), but its use and implementation are not mandatory right now. This document regulates new uses for RA from CDW, such as cycling pavements, back fill and bedding material in pipes, unpaved rural roads, and structural road layers, establishing the physical-mechanical and chemical properties required for RA for each of these uses. There is no reference to the use of SW in civil engineering applications in this catalogue. The technical specifications included in the CRA for bike lanes construction materials have been obtained from laboratory tests, so the construction of experimental sections is a key aspect to improve the technical specifications of this catalogue. The Spanish General Technical Specification for Road Construction (PG-3) [11] is the active regulation in Spain. The problem with the application of PG-3 is that the proposed limits have been established for natural aggregates and not for recycled aggregates, thus limiting the use of recycled aggregates [12].

To determine if SW and RA are adequate as granular unbound layers in low bearing capacity roads and if the limits of this catalogue [10] are valid, a real scale experiment is needed to verify its performance and evolution over time.

According to Jimenez [12] there are three types of RA that can be used on roads, including recycled concrete aggregates (RCA), recycled mixed aggregates (RMA) and recycled mixed ceramic aggregates (RMCA). The difference between RCA, RMA and RMCA are its composition. RCA have more than a 90 % of Rc (concrete) + Ru (unbound aggregates without mortar attached) and a less than a 10 % of Rb (ceramic) , RMA have more than a 70% of Rc + Ru + Ra (asphalt) and a less than a 30 % of Rb. Finally RMCA has less than a 70 % of Rc + Ru + Ra and more than a 30% of Rb. Lancieri et al. [13] completed a test with RMA as the unbound layer in two 200-metres long paved sections over two different subgrades classified as A-2-6 and A-7-8, respectively, in accordance with the American Association of State Highway and Transportation Officials (AASHTO) [14]. The elastic moduli for these recycled unbound layers over a period of eight years was calculated, and these materials had an increase in bearing capacity due to self-cementing and further traffic compaction.

Jiménez et al. [15] studied an experimental unpaved road with two different sections of 100 metres long each, with RMA as the granular subbase and RCA and NA as the granular base. The subgrade was classified as A-6 in accordance with AASHTO. Both recycled materials met all specifications required by PG-3 for use in structural layers, except the soluble salt content. Jimenez et al. [16] studied a second experimental road with non-selected RMA obtained with low embodied energy as the granular bases; NA was placed as the granular subbase and compared with RMA. The subgrade was classified as A-1-B according to AASHTO. The RA did not meet the limits for sulphur compounds and soluble salt content. Tavira et al. [17] studied a paved experimental road with three sections that was built with RMA mixed with natural excavation soil in the subbases and RMA in the base; NA was used in the bases and subbases. In all previous studies, the performance of NA was similar to that of RMA. SW was not used in these experimental roads due to its impurities; furthermore, according to previous studies, SW should be removed at the beginning of the recycling process [18].

The main purpose of this research is to study the feasibility of using low quality recycled mixed aggregates from CDW and the SW obtained in its processes as structural layer materials of a paved bike lane where the mechanical requirements are lower than for roads. Construction of an experimental bike lane could validate the use of these recycled materials, which do not satisfy the chemical and physical specifications to be used in roads [13]. Otherwise, these materials would end up in landfills. The elastic moduli of recycled materials are a basic parameter used to estimate pavement longevity in this research, obtained through backcalculation. With this RA moduli input, the equivalent thicknesses of pavement sections built with recycled materials or natural aggregates can be calculated. Full or partial replacement of natural materials by recycled materials can contribute significantly to reduce ecological footprints in road infrastructures [19]. To the best of our knowledge, there are no previous studies regarding the use of SW obtained from CDW as unbound layers materials in the construction of roads or bike lanes.

2 Materials and methods

2.1 CDW recycling procedure

The experimental bike lane (EBL) was built using two recycled materials from CDW: a recycled mixed aggregate (RMA-1) and a recycled mixed material from screening waste (RMSW-1). Fig. 1 shows the CDW process and collection points of the recycled materials. The first step after arrival of CDW was to reduce bigger fragments that could not be crushed, then primary screening (0/20 mm) removed the finest particles with more impurities and improved the quality of the recycled aggregates subsequently obtained. Then, RMSW-1 was collected. An impact crusher ground particles greater than 20 mm. The ground materials were screened by a 40-mm sieve. At this point, materials larger than 40 mm were returned to the impact crusher to reduce their size. After passing through the sieve, a magnetic belt conveyor was used to remove metallic elements. Finally, a blower removed light particles to obtain RMA-1.

Table 1 shows the composition of the recycled materials in accordance with UNE-EN 933-11 [20]. RMA-1 would be classified as a recycled mixed aggregate according to the catalogue of pavement and work units with RA from CDW (CRA) [10]. Based on its composition, RMA-1 could be used as the base course materials in paved bike lanes.

In accordance with the proposal of CRA use for the construction of paved bike lanes, materials used in subbase layers must contain a percentage of impurities less than 3% (X_1 + X_2), a quantity of floating particles less than 2 cm^3/kg, and a percentage of gypsum particles less than 1%. Due to the high content of impurities in the screening waste, RMSW-1 could not be used as subbase course materials in paved bike lanes.

2.2 Description of the test sections

The EBL was built on a section of a cyclist route that connects the urban area of the city of Córdoba (Spain) with the University Campus (Andalusia, Spain). It was not built beside any common roads as shown on Fig 2. The EBL had three sections of 100 m, 100 m, and 200 m for sections I, II and III, respectively. The structural layers were designed according to the design recommendations for bicycle lanes proposed in the catalogue of pavement and work units made with RA from CDW published by the Public Works Agency of the Regional Government of Andalusia (Spain) [10]. Fig. 3 shows the description of the three sections and the thicknesses of the structural layers. The surface course of all sections was made of 4 cm of asphalt concrete BBTM8B [11], it is a non-continuous bituminous mixture with a maximum aggregate size of 8mm . The base course of the second section was crushed limestone (CS-1). The recycled mixed aggregate (RMA-1) was used in the first and third sections. The subbase course was built with two different materials. Section I was made of a natural selected soil (SS-1). Material obtained from primary screening of CDW (RMSW-1) was used in sections II and III. Construction of the EBL lasted from October 2014 until February 2015.

2.3 Materials characterization

Materials used in the EBL were characterized according to the Spanish General Technical Specification for Road Construction (PG-3) [11] and the catalogue of pavement and work units with RA from CDW (CRA) [10]. Granular layers and the subgrade materials were collected according to UNE-EN 932-1 [21]. Test procedures met specifications of UNE-EN 932-2 [22].

2.3.1 Subgrade material

This material was tested to determine the following properties: plasticity index (UNE 103104:1993 and UNE 103103:1994) [23,24], sulphates content (UNE 103201:1996) [25], standard Proctor test (SPT) (UNE 103500:1994) [26], California Bearing Ratio (CBR) (UNE 103502:1995) [27], and free swelling and particle size distribution (UNE 103601:1996) [28].

2.3.2 Subbase and base materials

The following properties were tested: plasticity index according to UNE 103104:1993 and UNE 103103:1994 [23,24], the particle size distribution (UNE 103102:1995) [29], modified Proctor test (MPT) (UNE 103501:1994) [30], CBR index (UNE 103502:1995) [27], Los Angeles abrasion coefficient (UNE-EN 1097-2:2010) [31], the total Sulphur content and soluble salt (UNE-EN 1744-1:2010) [25], percentage of crushed particles (UNE-EN 933-35:1999) [32], and flakiness index (UNE-EN 933-3:2012) [33].

2.4 Field Testing during construction

2.4.1 Field density and moisture content

After setting every granular layer in place, field densities and moisture content were determined using a Trolex model 3440 surface moisture-density gauge according to ASTM D6938 [34]. This test is a quick and non-destructive technique for measuring water content and dry densities of unbound layers. A test was performed every 20 m. The maximum dry density and optimum moisture content of the modified proctor test was used to compare with the results obtained in the field.

2.4.2 Falling weight deflectometer (FWD)

Pavement deflections are commonly accepted as a state indicator of pavement structural condition [35]. A Dynatest Heavy Weight Deflectometer 8081 equipped with seven geophones was used. The geophones were located at 0, 300, 450, 600, 900, 1200, and 1500 mm from the loading plate. This equipment has been used in previous studies by Jimenez et al. [15,17,36,37], Tavira et al. [17] and Del Rey et al. [37]. A 450-mm diameter plate was used on the granular layers (bases and subbases), and a plate with 300 mm of diameter was used on the surfaced courses. Loads applied were 39.24 kN with a pressure of 246.47 kPa on the unbound layers and 49.05 kN with a pressure of 693.21 kPa on the asphalt concrete layer; these loads and configurations are regulated by the Technical Specifications for High-Performance Dynamic Monitoring Tests [38] from the Civil Works Agency of Regional Government of Andalusia. Deflections were obtained every ten metres along the three sections in accordance with ASTM D4694 [39]. According to the Spanish standard, temperature did not influence the measurement of the deflection located under the plate at a distance of 0 mm because asphalt concrete was below 10 cm of the thickness [35]. Deflections were measured after the completion of each layer and at the completion of the experimental section (February 2015). Twenty six months later, a new test was performed (April 2017).

2.5 Elastic modulus calculation

The moduli of the EBL pavement were obtained using Evercalc [40]. This software calculates the pavement structure moduli of the pavement layers through an iterative process that reproduces the mechanical performance under FWD loading, the method is described in detail by Tavira et al. [17]. Basically It compares the calculated deflections with the deflections measured on field, through an iterative process error is minimized after each step. A previous study made by Tarefner et al. [41] proved that Evercalc produced more consistent and accurate modulus values than Backfaa and Modulus software.

2.6 Description of external factors

Climate has a great influence in pavement layer behaviour. A local weather station collected precipitation and temperature values at coordinates in the Universal Transverse Mercator (341399, 4191480).

Fig. 4 shows the average monthly maximum and minimum temperatures from October 2014 to March 2017, indicating that there were no extreme temperatures. Fig. 5 shows that the highest rainfall collected was in November 2014 for a total of 153.6 mm.

3 Results and discussion

3.1 Physical and chemical properties of the materials

Table 2 shows the physical and mechanical properties of the unbound materials placed in the EBL as well as the requirements established by the Spanish specifications PG-3 and CRA [10]. Fig. 6 shows the particle size distribution of the unbound layer materials.

The fine percentage of SG-1 is 67.9%, and it would be classified as an A-6 according to AASHTO [14]. SS-1 would be classified according to AASHTO as an A3 [14] and RMSW-1 would be classified as an A4 [14]. RMA-1 and CS-1 would be classified as A-1-a [14].

Both natural materials (SS-1 and CS-1) came from limestone quarries, and all the physico-chemical properties fulfil the requirements of PG-3 [11] for use as subbase and base materials. Densities and CBR of SS-1 and CS-1 are higher than those of RMA-1 and RMSW-1. CBR of RMA-1 and RMSW-1 are 65.5% and 24%, respectively. The CBR value of RMA-1 is according to the values obtained by Jiménez et al. [12] and Del Rey et al. [37] for mixed recycled aggregates (40-90%), which meet the values of 40% specified for granular bases in CRA [10]. RMSW-1 showed similar values of CBR to those obtained in Tavira et al. [17], and RMSW-1 would be classified by its value as A-3 according to AASHTO [10,11] (CBR >5%).

Optimum moisture is higher in recycled materials than in natural materials, as shown in previous studies [15–17,42], due to the higher water absorption of recycled materials. RMA-1 had a Los Angeles coefficient of 39, which does not meet the limit of 35 required in the PG-3 for base materials, although this limit could be increased up to 40% in accordance with CRA [10]; RA from CDW, due to its origin, has higher abrasion values. According to previous literature, most RMA values should be under 45% [12,13]. In Los Angeles coefficient test all the attached mortar of recycled aggregate is powdered, apart from the abrasion suffered by the natural aggregate. For this reason, both properties are related, when attached mortar content is high, Los Angeles coefficient increases too [12].

Regarding chemical properties, the organic matter, soluble salt and gypsum content in subgrade (SG-1) was under 0.3%. The PG-3 limit was up to 0.2% content of the organic matter; RMA-1 and RMSW-1 have 0.92% and 1.10% organic matter content values, respectively. Organic matter is not a limiting property in road applications and has a typical range of 0.42-1.00% according to Jimenez [12], and on CRA [10], the organic matter is limited to 1% content for granular bases and subbases.

PG-3 limits soluble salt content to 0.2%. RMA-1 had a content of 3%, and RMSW-1 had a 4% soluble salt content. CRA [10] increases this limit to 2% content in subbases. Previous studies [12,15,16,18] showed that a soluble salt content of approximately 4% does not generate dimensional instability in unpaved rural roads, but further studies were needed to assure it with outdoor and traffic conditions. RMA-1 and RMWS-1 content of water soluble sulphates (SO_4) does not meet the CRA [10] limit of 0.7% for bases. These limits should be increased for bike lanes up to 1.3% for bases and 2% for subbases. The sand equivalent (27%) and particle size distribution (Fig. 6) in RMA-1 do not meet the PG-3 [11] and CRA [10] requirements due to its fine content. Previous studies of recycled materials used as unbound layers did not meet these limits either [15–17].

3.2 Quality control of compaction

Compaction is the main factor that influences the bearing capacity of unbound layers [43]. Moisture and water content were measured on each granular layer as well as on the subgrade. The degree of compaction was compared with the results of the reference proctor test. On the subgrade, the standard proctor test was used; on granular bases and subbases, the modified proctor test was considered. The limits for the degree of compaction are taken from PG-3 [11]. The Standard Proctor Test results must be over 100% on subgrades, while the Modified Proctor Test results must be over 95% on subbases and 98% on bases. Table 3 shows the average values and standard deviation values obtained on site.

Compaction meets in most cases with PG-3 [11] specifications; therefore, the construction of EBL was acceptable. Average values on subgrade were 104.5%, 103.2% and 102.8% for sections I, II and III, respectively. Regarding to subbases, SS-1 had a 96.2% degree of compaction on section I, while section II and section III were 104.3% and 99.0%, respectively, which meet the limits of PG-3 [11] (95%). All values for the bases were over 98% of the Modified Proctor Test, and the average values were 101.3%, 103.7% and 102.5% for sections I, II and III, respectively.

According to Table 3, the densities for RMSW-1 (sections II and III) are lower than in natural soil SS-1 (section I). In base layers, densities are also lower in recycled materials (RMA-1) than in crushed stone from the quarry (CS-1), as shown in Table 3. These results are in line with previous studies conducted by Jiménez et al. [12,15,16,36], Del Rey et al. [37] and Tavira et al. [17]. The moisture content values for RA are higher than in NA, and the densities are lower because the water absorption in RA is greater than in NA, as shown in previous studies [12,15–17,36,37]. The porosity of RA and its fine portion increase the exposed surface and water absorption, causing these results.

3.3. Falling weight deflectometer during construction

Table 4**Error! Reference source not found.** shows the mean (M) and standard deviation (SD) of the deflections and elastic equivalent moduli for every section and layer. The following equation proposed by Brown was used [44]:

$$\boldsymbol{E_0 = \frac{2\sigma_0 a(1-\mu_0^2)}{d_0}}$$

E = Elastic Equivalent modulus of the entire pavement system beneath the load plate.

a = Radius of the FWD plate.

σ = Pressure of the FWD impact load under the load plate.

d =Deflection at 0 mm from the centre of the FWD plate.

μ = Poisson’s ratio, value considered was 0.35.

The deflection and equivalent moduli values on the surface course, base and subbase have approximate values among the three sections. Tavira et al. [17] researched a road open to heavy vehicles in which recycled mixed aggregates were mixed with soil and used as the base and subbase granular layers. The results showed lower deflections and higher equivalent moduli because of the lower mechanical requirements in the EBL. Jiménez et al. [15] tested a selected mixed recycled aggregate on an experimental unpaved rural road. Using recycled concrete aggregates and crushed limestone as a reference, the deflections are lower in the rural road than those obtained in EBL. Jiménez et al. [16] also evaluated an experimental rural road by examining the performance of a recycled aggregate from non-selected CDW. Deflection results on granular bases were similar to those obtained in the EBL.

3.4. Field control of the evolution of the deflection and equivalent moduli

An analysis of variance (Anova) was conducted with the statistical software Statgraphics Centurion XVI (Version 16.1.18) to assess the significance of the effect of the two factors (section and date) on the surface course deflection. The results presented in Fig. 7 and Table 5 show that there are not significant differences in the mean deflections experienced on each of the sections (p-value >0.05). However, dates had significant influence on sections I and III but did not influence section II. On three sections, the deflection values decreased after two years; this good behaviour occurred because of the light traffic supported by the EBL and the drainage provided by the asphalt layer that helped avoid loss of the granular layers.

Fig. 8 and Table 6 show the Anova of the equivalent modulus evolution between February 2015 and April 2017. Equivalent moduli consider the stiffness of all layers that compose the pavement. The results indicate that there is no significant influence on any section for any date on their equivalent moduli (p-value >0.05). The p-values are under 0.05, so there is a statistically significant difference among dates for sections I and III but not for section II. The moduli values increased after 26 months by 36%, 13% and 34%, respectively, for sections I, II and III. Jiménez (2013) describes that the bearing capacity of recycled mixed aggregates from CDW increases over time (demonstrated under laboratory conditions). This author attributes this improvement over time to the pozzolanic reactions occurring between the silica and alumina of the ceramic fines and the hydrated portlandite of the cement, or to certain hydraulic properties that remain in the cement of the concrete and attached mortar. This finding has been tested on a real scale in this research. The equivalent moduli are higher than those obtained by Del Rey et al. [37]; these authors studied a three section experimental road in which non-selected and selected mixed aggregates were compared with natural aggregates. The results showed a mean of 116.9 MPa for the elastic equivalent moduli in the non-selected aggregates, 135.2 MPa in selected CDW, and 160.4 MPa in the NA section.

3.5. Young moduli calculation of bases and subbases

The deflection basins were analysed with Evercalc [40]; this software back-calculates the moduli through an iterative process, where the measured data are compared with the theoretical data. The process will run until it finds convergence with limited error. As shown in Fig. 9 and Table 7, the evolution of the selected soil SS-1 and RMSW-1 is not statistically significant among materials studied with the ANOVA analysis (p-value >0.05). RMSW-1 had a mean value of 201 MPa, while SS-1 had a mean value of 220 MPa. Moduli values obtained for RMSW-1 indicate that this material may be used as a selected soil (PG-3) [11], and its modulus should be catalogued as A-3 according to AASHTO [14]. Previous studies [13,17] showed similar values of RMSW-1 (122-200 MPa), but subbases in a previous study [17] indicated soluble sulphates content below 1%. Table 7 shows an increased moduli over time of both materials. The moduli increased after 26 months to 9.58% *versus* 6.1% for SS-1. This moduli value increase for the mixed recycled materials can be explained by certain latent hydraulicity of the cement particles or by various pozzolanic activities of the ceramic particles [12].

Fig. 10 and Table 8 show moduli for granular bases, and there is no statistically significant difference of moduli between CS-1 and RMA-1 (p-value >0.05). The mean moduli of RMA-1 and CS-1 are 424 MPa and 421 MPa, respectively. Moduli values obtained for RMA indicate that this material is acceptable to use as a granular base (PG-3) [11] and can be catalogued as A-1-a according to AASHTO [14]. Previous studies [13,17] showed lower values (235-379 MPa) of RMA than for RMA-1. Other experimental roads [13,37] showed that RA with a content of a 40% mortar and cement can gain resistance due to re-cementation [12]. After 26 months, moduli increased on both materials as follows: RMA-1 had an increase of a 5.55%, and CS-1 had an increase of 2.7%.

Moduli for these recycled materials are used to help calculate the equivalent thickness needed to replace NA. One centimetre of RMSW-1 can replace 1 cm of selected soil, and 1 cm of RMA-1 can replace 1 cm of crushed stone.

4 Conclusions

This research focus on the mechanical behaviour of an experimental bike lane made with recycled mixed aggregates obtained from CDW (RMA-1) and its screening wastes (RMSW-1). In accordance with AASHTO, the RMA-1 can be classified as A-1-a, and RMSW-1 can be classified as A-4 because of its fine fraction.

According to the behaviour of the recycled materials used on this experimental bike lane, the following limits established in the technical specifications could be modified for granular bases in bike lane construction: organic matter content could be increased to 2%; sulphate content could be increased to a 2.5%; soluble salts content could be increased to 4%; Los Angeles Abrasion could be increased to 40%; and equivalent sand could be decreased to 25%.

Bearing capacity and its evolution over time is more than acceptable for the type of road studied. It exceeds the limits established by regulations for the construction of bike lanes. Moreover, its bearing capacity increased after two years to ensure the use of these two recycled materials as granular layers in bike lanes.

Young's moduli of recycled materials placed on site were calculated, which is a key aspect for pavement design. Subbase layers made with screenings wastes obtained a mean modulus of 200 MPa, while granular bases made with recycled aggregates obtained a mean modulus of 420 MPa. Both recycled materials performed as well as natural aggregates and soils used in the experimental bike lane. RMA and RMSW can replace crushed stone (A1-a) and selected soil (A-3), respectively. Recycled aggregates obtained an equivalent thickness with crushed stone at a ratio of 1:1; therefore, recycled aggregates can replace natural aggregates with the same volume of material. Selected soil (A-3) and screening wastes also have an equivalent structural thickness.

This study promotes new uses for recycled materials from CDW demonstrating the feasibility of using mixed recycled aggregates and its screening wastes as granular bases and subbases in paved bike lane construction. The low mechanical requirements of this type of infrastructure would increase the limit of various limiting properties, such as organic matter content, total sulphur content, soluble salt content and water soluble sulphates.

The findings of this study can reduce natural aggregate extraction from rivers and quarries, significantly minimize the ecological footprint, prevent illegal and landfill deposits of the fine fraction of CDW, and meet the limits of the European Waste Framework Directive. This demonstrates the practical relevance of this study to promote new uses for recycling aggregates and its screening wastes in the construction sector.

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TABLE CAPTIONS

Table 1 Composition of the mixed recycled aggregates (UNE-EN-933-11:2009)

Table 2 Physical, mechanical and chemical properties of EBL's unbound materials

Table 3 % Moisture content and density

Table 4 Deflections and equivalent moduli during construction

Table 5 Anova analysis of defections on surface course

Table 6 Anova analysis of equivalent moduli on paved EBL

Table 7 Anova analysis of granular subbases moduli

Table 8 Anova analysis of granular bases moduli

FIGURE CAPTIONS

Fig. 1. Recycling process of CDW

Fig. 2 Images of the Experimental Bike Lane

Fig. 3 Cross sections of the Experimental Bike Lane

Fig. 4 Average monthly maximum and minimum temperatures

Fig. 5 Monthly total precipitation (mm) from October 2014 – March 2017.

Fig. 6 Particle size distribution.

Fig. 7 Deflection Evolution on surface course

Fig. 8 Equivalent moduli on paved EBL

Fig. 9 Moduli of granular subbases

Fig. 10 Moduli of granular bases

Figure

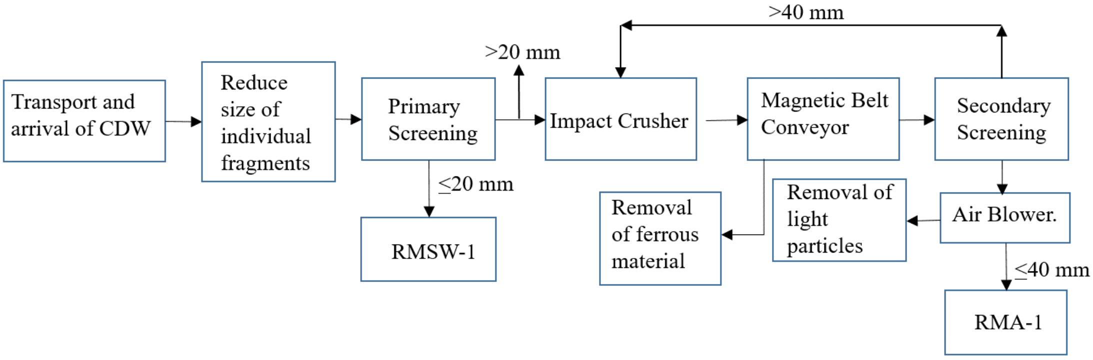
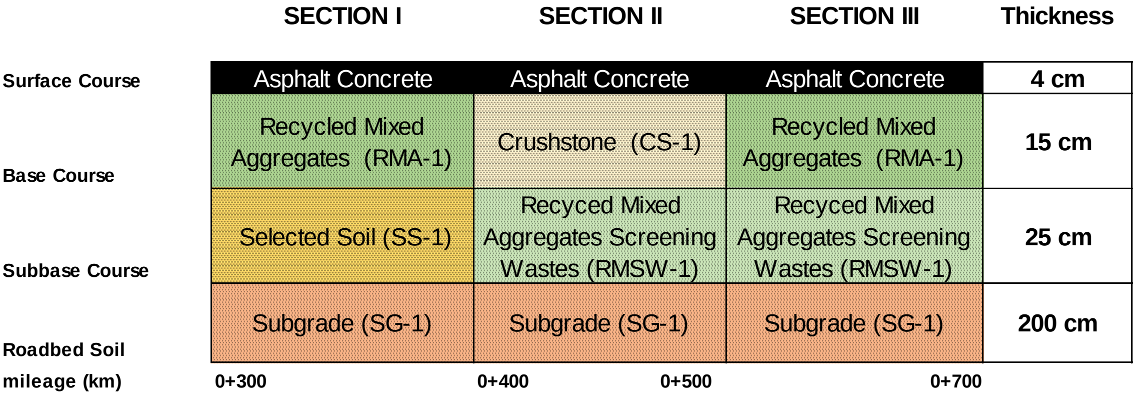


Fig. 1. Recycling process of CDW

Fig. 2 Images of the Experimental Bike Lane



	SECTION I	SECTION II	SECTION III	Thickness
Surface Course	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	4 cm
Base Course	Recycled Mixed Aggregates (RMA-1)	Crushstone (CS-1)	Recycled Mixed Aggregates (RMA-1)	15 cm
Subbase Course	Selected Soil (SS-1)	Recyced Mixed Aggregates Screening Wastes (RMSW-1)	Recyced Mixed Aggregates Screening Wastes (RMSW-1)	25 cm
Roadbed Soil	Subgrade (SG-1)	Subgrade (SG-1)	Subgrade (SG-1)	200 cm

mileage (km) 0+300 0+400 0+500 0+700

Fig. 3 Cross sections of the Experimental Bike Lane

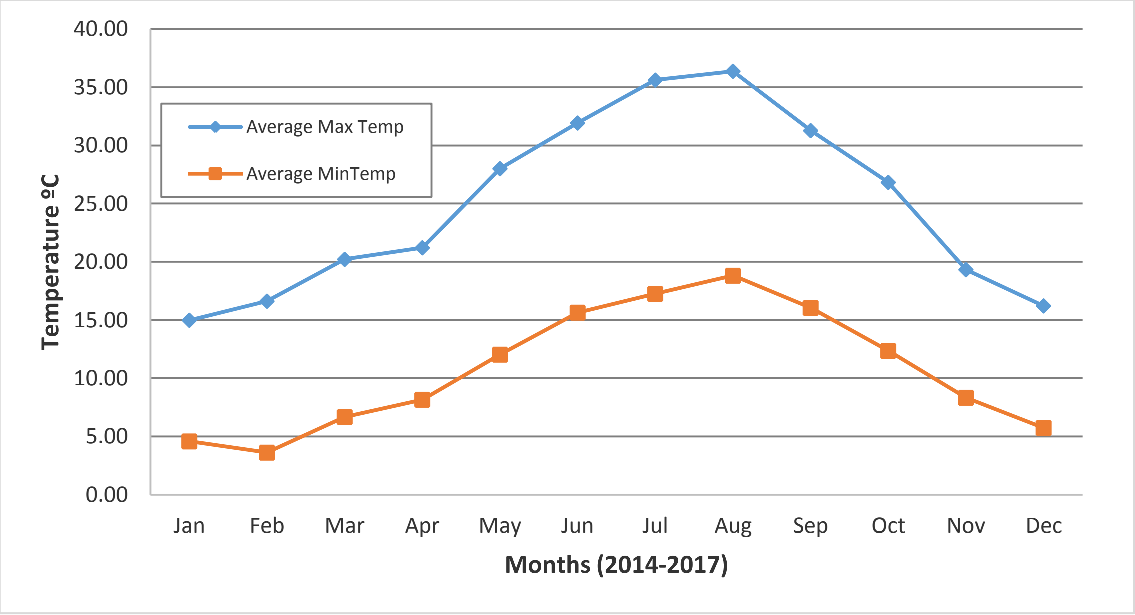


Fig. 4 Average monthly maximum and minimum temperatures

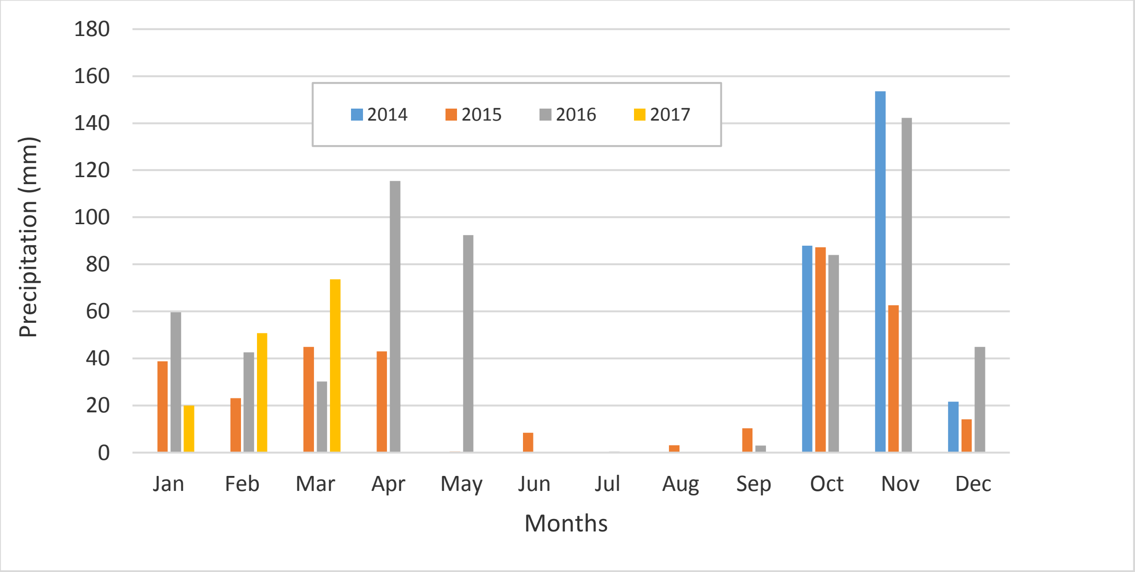


Fig. 5 Monthly total precipitation (mm) from October 2014 – March 2017.

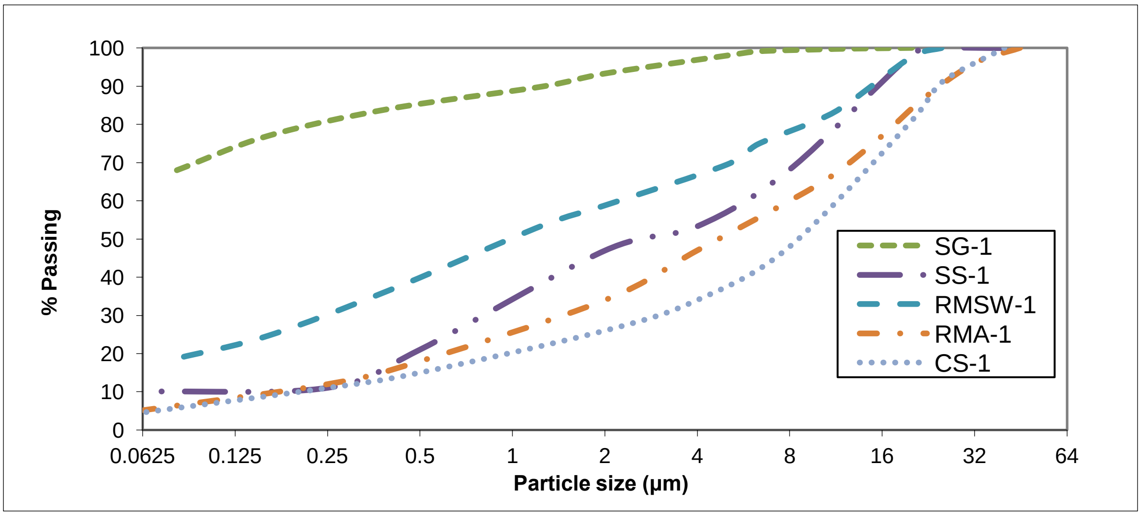


Fig. 6 Particle size distribution.

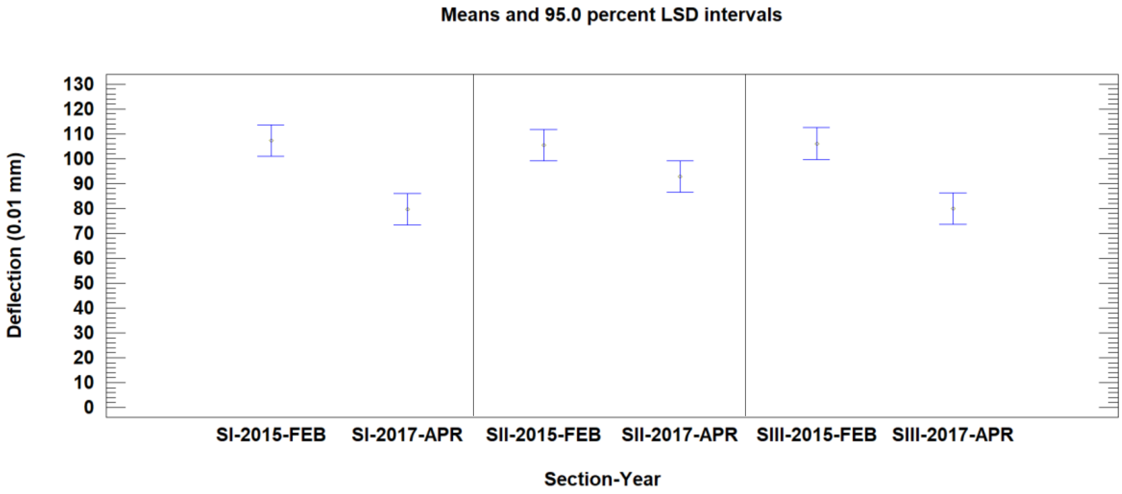


Fig. 7 Deflection Evolution on surface course

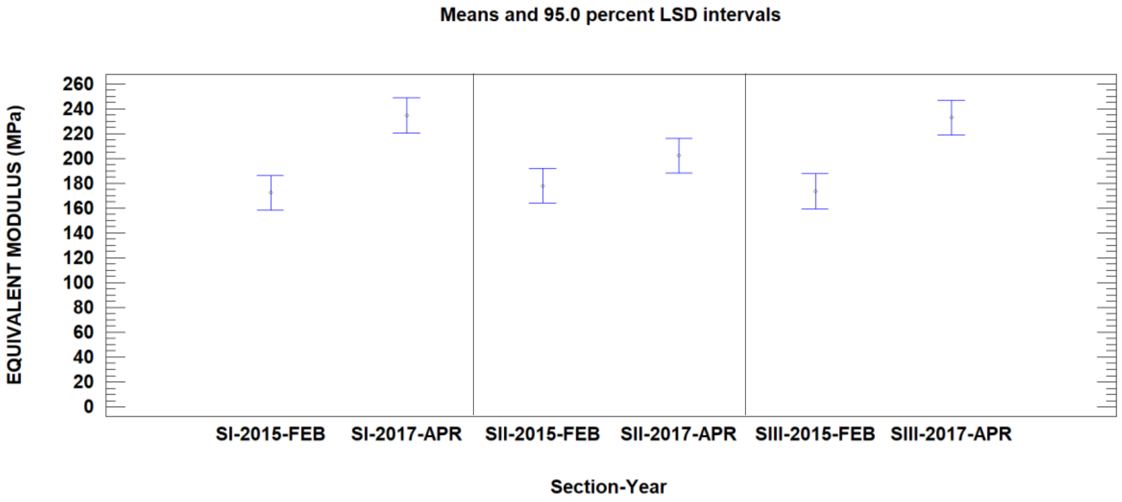


Fig. 8 Equivalent moduli on paved EBL

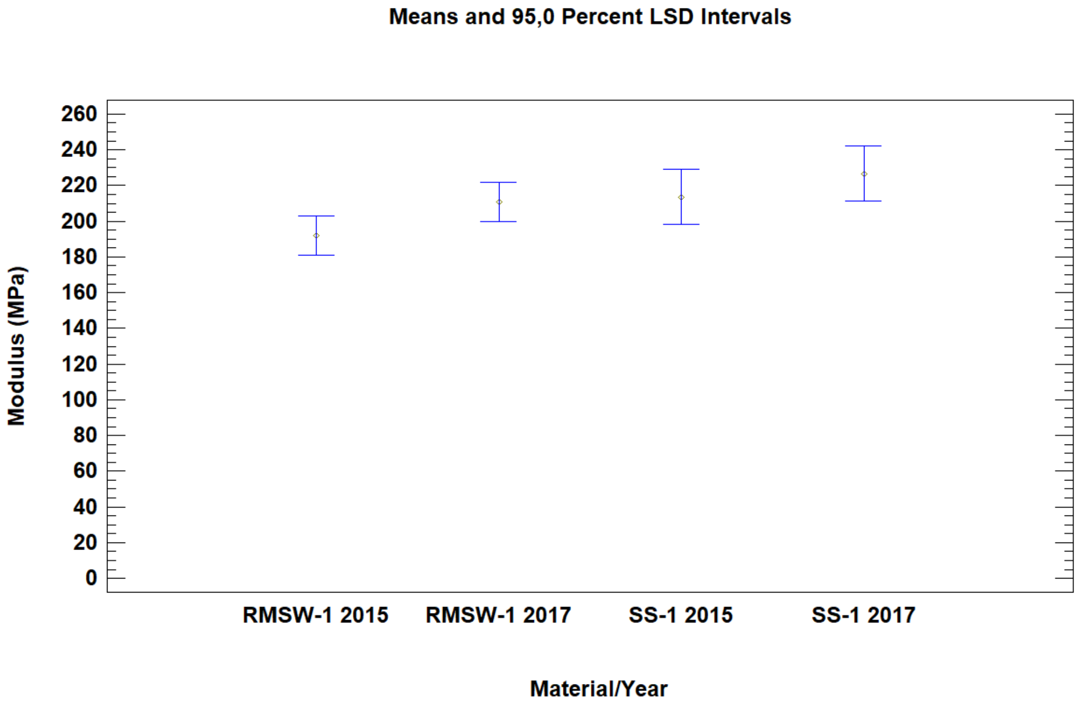


Fig. 9 Moduli of granular subbases

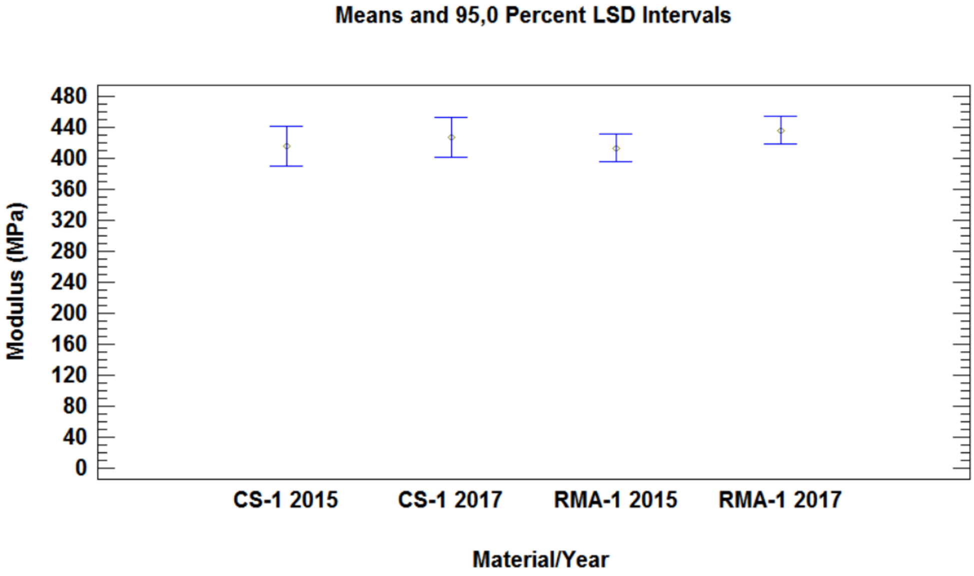


Fig. 10 Moduli of granular bases

Table 1 Composition of the mixed recycled aggregates (UNE-EN-933-11:2009)

Compositions	RMSW-1	RMA-1
% R_A (Asphalt)	2.3	1
% R_B (Ceramics)	17.3	24
% R_C (Concrete and Mortar)	67	60
FL (Floating particles) (cm^3/kg)	2.7	0
% R_U (Unbound aggregates)	8	14
% X_1 (Gypsum)	1.5	0.8
% X_2 (Wood, plastic and metals)	1.2	0.2

Table 2 Physical, mechanical and chemical properties of EBL's unbound materials and PG-3 and CRA requirements for mixed recycled aggregates

Properties		SG-1	SS-1	RMSW-1	RMA-1	CS-1	PG3 limits		CRA limits		Standards
							Subbase (SS)	Base (CS)	Subbase (RSS)	Base (RMA-I)	
Water absorption (%)	>4 mm	-	-	8.9	8.0	-	-	-	-	< 9	UNE-EN 1097-6:2014
	<4 mm	-	-	11.2	9.6	-	-	-	-	< 12	UNE-EN 1097-6:2014
Density-SSD (g/cm^3)	>4 mm	-	-	2.02	2.13	-	-	-	-	-	UNE-EN 1097-6:2014
	<4 mm	-	-	2.34	2.32	-	-	-	-	-	UNE-EN 1097-6:2014
Max. Size (mm)		12.5	25	20	32	25	100	32	100	40	UNE 103101:1995
% passing sieve # 0.08		67.9	4.6	18.7	5.2	4.6	< 25	-	< 25	0-11	UNE 103101:1995
Liquid Limit		30.7	-	-	-	-	< 30	-	< 30	-	UNE 103103:1994
Plastic Limit		19.2	-	-	-	-	-	-	-	-	UNE 103104:1994
Plastic Index		11.5	-	NP	NP	NP	< 10	NP	< 10	NP	UNE 103104:1993
Sand equivalent (%)		-	-	-	27	42.2	-	> 30	-	> 30	UNE-EN 933-8:2000
Los Angeles (%)		-	-	-	39	28	-	< 35	-	< 40	UNE-EN 1097-2:2010
Flakiness index (%)		-	-	-	13	8	-	< 35	-	< 35	UNE-EN 933-3:2012
Crushed particles (%)		-	-	-	100	100	-	≥ 50	-	≥ 50	UNE-EN 933-35:1999
Max. Dry Density (Mg/m^3)		1.85	2.06	1.87	1.84	2.11	-	-	-	-	UNE 103501:1994
Optimum Moisture (%)		12.7	9.1	12.6	14.7	7.4	-	-	-	-	UNE 103501:1994
C.B.R. (%)		5.9	26.4	24	65.5	78.7	≥ 20	-	≥ 20	> 40	UNE 103502:1995
Free swelling (%)		0.6	-	-	-	-	-	-	-	-	UNE 103502:1995
Organic matter (%)		0.27	0.20	1.10	0.92	-	< 0.2	-	< 1	< 1	UNE 103204:1993
Gypsum - $CaSO_4$*H_20 (%)		0.30	0.47	1.5	0.84	-	< 0.2	-	< 2	-	UNE-EN 1744-1:2010
Total Sulphur content SO_3 (%)		-	-	-	0.9	-	-	< 0.7	-	< 1.3	UNE-EN 1744-1:2010
Soluble salt content (%)		0.30	0.0	4.0	3.0	-	< 0.2	-	< 2	-	UNE-EN 1744-1:2010
Water soluble sulphates SO_4 (%)		-	0.13	2.02	1.36	-	-		-	< 0.7	UNE 103201:2003

The CBR tests were carried out with laboratory samples compacted at their corresponding maximum dry density of Modified Proctor and 4-day soaked conditions.

SS: selected soils, CS: crushed stone, RSS: recycled selected soils, RMA-1: recycled mixed aggregates

NP: No Plastic

Table 3 % Moisture content and density

	Subgrade			Subbase			Base		
Average	**Dry Density (Mg/m^3)**	**Moisture (%)**	**Compaction (%SPT)**	**Dry Density (g/cm^3)**	**Moisture (%)**	**Compaction (%MPT)**	**Dry Density (Mg/m^3)**	**Moisture (%)**	**Compaction (%MPT)**
Section I	1.93 ± 0.05	7.36 ± 1.28	104.54 ± 2.47	1.98 ± 0.02	4.32 ± 0.87	96.2 ± 0.96	1.86 ± 0.03	9.84 ± 1.57	101.29 ± 1.66
Section II	1.91 ± 0.05	6.72 ± 0.91	103.24 ± 2.88	1.95 ± 0.08	10.86 ± 1.21	104.26 ± 4.29	2.19 ± 0.02	4.06 ± 0.17	103.7 ± 0.82
Section III	1.9 ± 0.06	8.99 ± 2.65	102.75 ± 3.08	1.85 ± 0.06	10.04 ± 0.57	99.02 ± 3.15	1.89 ± 0.04	11.41 ± 0.91	102.49 ± 2.38

Table 4 Deflections and equivalent moduli during construction

		Section I				**Section II**				**Section III**			
		Deflections (0.01 mm)		Equivalent moduli (MPa)		Deflections (0.01 mm)		Equivalent moduli (MPa)		Deflections (0.01 mm)		Equivalent moduli (MPa)	
	Date	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)
Surface course	06/02/2015	107.26	12.66	172.41	21.34	105.41	19.11	178.05	30.29	106.12	10.63	173.60	18.05
Base	14/12/2014	147.94	34.27	69.21	16.16	153.31	35.10	66.95	16.58	144.63	24.69	69.06	11.22
Subbase	24/11/2014	180.88	37.76	55.55	9.96	196.85	26.18	50.01	6.16	172.10	24.37	57.82	9.81

Table 5 Anova analysis of defections on surface course

		Factor										
		Composition of Sections			Date							
Properties	Factor Levels	Section I	Section II	Section III		Section I		Section II		Section III		
Deflections (0.01 mm)	p-value	0.4937				0.0001		0.1372		0.0000		
	M	93.44	99.17	93,02	Factor Levels	M	SD	M	SD	M	SD	p-value
	SD	18.84	18.58	17.07	feb-15	107.26	12.66	105.4	19.11	106.12	10.63	0.9598
					apr-17	79.62	12.81	92.94	16.66	79.92	10.99	0.0623

M=Mean

SD=Standard deviation

Table 6 Anova analysis of equivalent moduli on paved EBL

		Factor										
		Composition of Sections			Date							
Properties	Factor Levels	Section I	Section II	Section III		Section I		Section II		Section III		
Equivalent Modulus (MPa)	p-value	0.4937				0.0002		0.1270		0.0002		
	M	203.5	190.19	203.21	Factor Levels	M	SD	M	SD	M	SD	p-value
	SD	43.54	35.29	41.38	feb-15	172.41	21.34	178.05	30.29	173.61	18.05	0.8562
					apr-17	234.59	37.39	202.33	37.21	232.81	36.64	0.1106

M=Mean

SD=Standard deviation

Table 7 Anova analysis of granular subbases moduli

		Factor						
		Composition of Sections		Date				
Properties	Factor Levels	RMSW-1	SS-1		RMSW-1		SS-1	
Modulus (MPa)	p-value	0.0552			0.094		0.4287	
	M	201.38	220.19	Factor Levels	M	SD	M	SD
	SD	34.70	35.84	feb-15	192.19	36.87	213.64	48.86
				apr-17	210.58	30.56	226.73	15.12

M=Mean

SD=Standard deviation

Table 8 Anova analysis of granular bases moduli

		Factor						
		Composition of Sections			Date			
Properties	Factor Levels	RMA-1	CS-1		RMA-1		CS-1	
Modulus (MPa)	p-value	0.8449			0.2542		0.5455	
	M	424.22	421.19	Factor Levels	M	SD	M	SD
	SD	62.58	40.68	feb-15	412.81	71.68	415.48	52.18
				apr-17	435.62	51.24	426.88	26.41

M=Mean
SD=Standard deviation

Figure-1

Figure-2