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ORIGINAL ARTICLE

Analysis of adequacy of recycling the São Paulo Metropolitan Ring Road concrete pavement as new pavement

Análise da adequação da reciclagem do pavimento de concreto do Rodoanel Metropolitano de São Paulo como novo pavimento

José Tadeu Balbo[a]
Ester Tseng[b]

[a]Universidade de São Paulo – USP, Escola Politécnica, Departamento de Engenharia de Transportes, São Paulo, SP, Brasil
[b]Transportation Engineering Solutions and Technologies Inc., Champaign, IL, United States of America

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Abstract: The west section of the Governor Mário Covas São Paulo Metropolitan Road Ring was opened to traffic in 2002. The original pavement was a jointed plain concrete pavement with dowelled joints and a design flexural strength (or modulus of rupture) of 4.5 MPa. Premature failure of the concrete slabs was observed not only by engineers and users, but also reported by the media. Concrete slabs soon started being demolished and replaced. Many of the removed slabs were taken to a nearby recycling plant for crushing. However, the resulting recycled concrete aggregate was not used in the manufacturing of the new slabs. There were concerns that the potential presence of detrimental chemical substances had caused the early deterioration of the slabs. If that were true, using recycled aggregates obtained from the original concrete could result in the same issues in the new mix. This paper describes a feasibility study on recycling the original concrete for use as aggregate in new concrete slabs. The first goal was to verify the presence of fluorite as detrimental substance in the existing concrete because there was a suspicion among concrete technologists engaged on mixture design during the construction. Chemical analysis using X-ray fluorescence spectrometry did not show the presence of chemical components detrimental to concrete durability. Therefore, the second goal was to accept the material for recycling and discuss mix proportions, strength, stiffness, fracture toughness, and fatigue. Although some of the concrete properties were affected by the inclusion of recycled aggregates in the mix, the results indicate that it is possible to use recycled aggregates produced from the original concrete to cast new concrete slabs, however requiring greater thicknesses. The fatigue performance of recycled mixtures points out the demand for thicker and eventually more expansive design solutions.

Keywords: concrete pavement, concrete recycling, flexural strength, fracture, fatigue, durability.

Resumo: O trecho oeste do Rodoanel Governador Mário Covas foi aberto ao tráfego no ano de 2000. O pavimento era originalmente composto por placas de concreto com barras de transferência, com módulo de ruptura de projeto 4.5 MPa. Falhas prematuras foram observadas não somente por engenheiros e usuários, mas foram também relatadas pela imprensa. Placas de concreto começaram a ser demolidas e substituídas. Muitas das placas removidas foram levadas a uma planta de reciclagem local para britagem. Entretanto, os agregados produzidos não foram utilizados na produção das novas placas de concreto. O primeiro objetivo foi verificar a presença de fluorita como substância prejudicial no concreto existente, pois era uma suspeita entre os tecnologistas de concreto envolvidos no projeto de mistura durante a construção. As análises químicas por espectrometria de fluorescência de raios X não evidenciam a presença de componentes químicos prejudiciais à durabilidade do concreto. Portanto, o segundo objetivo foi aceitar o material para reciclagem e assim discutir proporções da mistura, resistência, rigidez, tenacidade à fratura e fadiga. Este documento apresenta um estudo de viabilidade da utilização de agregados reciclados na produção de novas placas de concreto, contudo mais espessas. O estudo inclui discussões sobre as proporções de mistura, resistência mecânica, fratura, fadiga, e composição química. A análise química com espectrometria de fluorescência de raios-X não detectou a presença de compostos químicos prejudiciais a durabilidade do concreto. O desempenho à fadiga de misturas recicladas impõe demandas por soluções de projeto mais espessas e custosas.

Palavras-chave: pavimento de concreto, reciclagem de concreto, módulo de ruptura, fratura, fadiga, durabilidade.

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Corresponding author: José Tadeu Balbo. E-mail: jotbalbo@usp.br
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1 INTRODUCTION

The first section of the São Paulo Metropolitan Ring Road (SSMRR) was completed in October 2002, extending over 32 km with three to four lanes in each direction. The SSMRR was expected to reduce truck traffic in the main arterial roads by 25%, as well as to reduce vehicular pollutants inside urban areas.

The original pavement consisted of conventional jointed plain concrete slabs 240-mm thick over a roller-compacted concrete (RCC) base 150-mm thick. The subgrade comprised of an expansive granite residual soil subgrade. Traffic studies predicted an average of 134,209 trucks per day by 2020 [1]. The pavement was designed following the Portland Cement Association (PCA) 1984 method [2]. A more consistent methodology for the design of plain concrete pavements (1998 Supplement to the AASHTO Guide for Design of Pavement Structures) was already available at that time but was not used. The PCA 1984 methodology adopted does not consider thermal gradients in tropical environments [3]. Moreover, the fatigue failure criteria were developed during the 60's in the State of Illinois, USA, where a different concrete mix design concept was used.

A few months from opening to traffic, pavement performance issues started. Cracked and divided slabs were observed in all lanes, including the left car lane, requiring removal and reconstruction of several slabs. Figure 1 shows the removal of deteriorated slabs in 2003. These slabs had developed severe longitudinal cracks near the edge and transverse cracks near the joints, resulting in an uneven pavement surface.

Figure 1. Slabs removal at left lanes at kilometer post (KM) 22 in 2003. (Reproduction: Folha de São Paulo newspaper).

There are no available records clarifying the potential causes for these early distresses. Informal conversations within the concrete community suggested several possible causes, including:

a) inconsistency in saw cutting depths (which were visually observed) and poor curing, resulting in shrinkage cracks parallel to longitudinal and transverse joints;
b) deficiencies in RCC base thickness, which were observed in some sections;
c) possible delays in saw cutting the joints (not verified);
d) possible modulus of rupture below specification limits (not verified);
e) possible high fluorite (CaF_2) content within the hydraulic binder used for the mixes, accelerating degradation (not verified);
f) insufficient design slab thickness (discussed in the following paragraph); and
g) inappropriate design thickness (formerly verified).

Cervo et al. [2] developed a local concrete fatigue design criterion, which takes into consideration thermal effects through finite element modeling. According to this design criteria, for a 20-year design life and assuming the same concrete modulus of rupture used in the original design (4.5 MPa), the required concrete slab thickness would be 260-270 mm, which is 20-30 mm more than the constructed thickness. Therefore, the insufficient pavement thickness may have contributed to the early appearance of cracks. Nevertheless, insufficient slab thickness does not affect the potential to recycle the concrete.

Performance issues persisted throughout the life of the pavement. In several locations, the slabs could be seen moving upward and downward with traffic, indicating the presence of voids under the slabs. These voids are believed to be a result of premature deterioration of the RCC. In some sections, transverse cracks developed at mid-slab. Figure 2 shows the injection of cement slurry under the concrete slabs to fill voids and control vertical movements.

In 2014, the injection of cement slurry was halted due to the high costs and traffic delays involved. The pavement then received a hot mix asphalt (HMA) overlay – a blacktopping. However, reflection cracks appeared in the HMA surface over underlying joints and concrete cracks. The HMA overlay did not mitigate the issues related to the presence of voids under the concrete slabs. Therefore, the removal of the original concrete slabs is still being considered in some areas.

Figure 2. Cement slurry injection at KM 30 in 2011.

The first study on the possibility of recycling the existing distressed SSMRR concrete pavement to build new concrete pavements was presented by Tseng and Balbo [4], regarding preliminarily the flexural strengths and stiffness of recycled mixtures. The current study includes additional information from laboratory tests carried out from 2010 to 2019, when the entire west section of the SSMRR was overlaid with a high-performance asphalt concrete.

One of the major concerns raised on the potential of recycling the concrete was the suspected presence of fluorite, a common mineral in carbonated (lime) rocks used in the manufacture of Portland cement. If present in concrete, fluorite could lead to harmful chemical reactions in the new concrete, compromising its durability. Therefore, as part of the study presented herein, the chemical composition of the concrete was investigated through electron microscopy images and spectroscopy.

The study was independent from the former state road operator – Highway Development Co. (DERSA) – and from the private operator. The results are open to the public due to its intrinsic interest.

2 RECYCLING CONCRETE PAVEMENTS: SHORT LITERATURE REVIEW

The past technical literature was rich on demonstrating the feasibility of the use of recycled concrete pavements as well recycled concretes in a general manner for the preparation of green (sustainable) concrete mixtures for the construction of new pavements that requires a huge consumption of material [5], [6] with several mixture proportions of recycled concrete aggregates discuss the adequacy of several proportions of blended new and recycled aggregates to reach acceptable performances for its use in concrete pavements. Nonetheless, Fanijo et al. [7] more recently stressed again about the effects of bonded mortar in resulting high absorption characteristic and reduced specific gravity of the recycled concretes which can impair some desirable properties for concrete pavements like ITZ conditions affecting fatigue resistance to cyclic loads. Given such an issue, Wang et al. [8] discussed on the developed methods along decades to improve ITZ and avoid excessive microcracks at this interface due to recycled aggregate porosity.

In the past twenty years several field real works in highways were prone to allow engineers to understand the recycled concrete performance and provide the required adjustments time after time. Krenn and Stinglhammer [9] presented one of the first studies on the construction of concrete pavements incorporating recycled concrete aggregates from older concrete pavements built even before the Second World War. The recycled aggregates were obtained from a concrete pavement more than 30 years old. In 1989-1990, about 50% of the A1 highway, linking Vienna to Salzburg, was rebuilt using recycled aggregates with nominal maximum aggregate size (NMAS) 4 mm to 32 mm, and natural sand (NMAS 4 mm). The recycled concrete mix consisted of 350 kg/m^3 of ordinary Portland cement, 700 kg/m^3 of virgin sand, 1,150 kg/m^3 of recycled concrete aggregates, and 0.245 kg/m^3 of air entrainer, with a water-cement ratio of 0.41. The project resulted in savings of approximately 205,000 metric tons of virgin gravel. In addition, 30,000 long-distance truck trips were avoided because the recycling process took place at the construction site. Cost savings of 10% were estimated compared to the use of conventional concrete.

Several projects for concrete pavements built with recycled aggregates from concrete highways in USA disclosed good performance, as reported by Cuttell et al. [10] reported several successful case studies in the United States (U.S.) where the concrete pavement was built using recycled concrete aggregates (from older concrete pavements), including nine highways and sixteen test sections within five US states. The main observations were:

i. The use of recycled concrete aggregates containing less mortar from the original (old, crushed) concrete resulted in better performing pavements.
ii. The effect of variation in the fineness modulus were not perceived, although a previous study by Yrjanson [11] indicated that the inclusion of recycled fine aggregates could influence concrete strength.
iii. The recycled concrete aggregate particles had an apparent specific gravity 2 to 3 kN/m^3 below the apparent specific gravity of the virgin aggregates used in control sections. This was attributed to the presence of old, less dense mortars within the recycled aggregate particles.
iv. There was a clear reduction in workability with the use of recycled concrete aggregates, which was attributed to the angularity, roughness, and porous surface of the recycled concrete particles. To improve workability, it was suggested to limit fine recycled aggregates content (to no more than 25%), use plasticizers, and/or incorporate fly ash to partially recycled aggregate voids.
v. Pavements containing recycled aggregates with limited recycled fine content resulted in higher compressive strength than control sections, based on testing conducted on field cores.
vi. Concrete mixes with recycled aggregates resulted in lower modulus of elasticity, due to the higher porosity of aggregates. Ricci and Balbo [12] presented similar results for RCC using 50 to 100% recycled coarse aggregates and 50% recycled fine aggregates. The modulus of elasticity of RCC containing 100% recycled coarse aggregates was 50% of the modulus of a control RCC.
vii. The coefficient of thermal expansion was higher for the recycled concrete mixes when compared to control mixes. This should be taken into consideration when designing the pavement.

More than a decade after Cuttell et al. [10] presented the study on recycled concrete mix properties, Sturtevant [13] evaluated the performance of the pavements containing recycled aggregates compared to control sections based on distresses, riding quality, and structural assessment. The recycled concrete pavements performed similarly to the control sections. The authors attributed the success to the use of recycling techniques that eliminated a large portion of the original concrete mortar from the surface of the recycled aggregates. They recognized, however, that by removing the old mortar from the recycled aggregates, not all the original concrete is recycled. When aggregates were crushed to a NMAS of 25 mm, 55 to 65% of the existing concrete was incorporated, whist when the aggregates were crushed to a NMAS of 38 mm, the percentage of incorporated material increased to 80%. Eliminating recycled fines reduces the risk of problems with workability, durability, and strength of the concrete. The only project where no specific measures were in place to eliminate the old mortar from the recycled aggregates ('Minnesota 4-1') experienced early cracking, resulting in the worst performance among the sections included in the study.

According to the U.S. Department of Transportation [14] the main problems that had to be overcome when using recycled aggregates from concrete pavements were: (a) workability problems related to the high water absorption of the recycled aggregates; (b) the increase in creep and shrinkage; (c) strength loss if excessive recycled fines are used; and (d) the appearance of corner cracks in harsh winter climates when the NMAS is greater than 25 mm. USDOT recommends limiting the quantity of recycled fine aggregates to no more than 30% of the total fine aggregate content.

As discussed above, many studies confirm that the use of recycled concrete coarse aggregates in a new concrete pavement can result in durable, resilient, and resistant pavements. The use of recycled concrete fine aggregates, however, may adversely affect pavement performance if used in high proportions. Several studies showed that recycled concrete fines substantially reduced workability and strength, making the concrete mix impracticable. Several authors recommend limiting recycled concrete fine aggregates to no more than 25 to 30% of the total fine aggregate content [9], [15]. The adverse effects of the recycled concrete fine aggregates are related to their composition, since most of these fines comprise the original concrete cement paste, which present high water absorption (6% to 12%) that cause significant increase in concrete shrinkage and expansion (Hendricks [15] *apud* Vancura et al. [16]). In Germany, fines generated during concrete crushing are normally used in frost protection layers and cement-treated sub-base layers [15].

Nevertheless, a highway in Switzerland incorporating 100% recycled concrete aggregates was reported to perform favorably. This success was attributed to the fact that the aggregates were separated into four fractions, avoiding particle segregation, and the particles were saturated in water 48 hours before mixing. The mixture also incorporated a plasticizer, an air-entraining agent, and silica fume [17]. Other studies reported success when replacing up to 50% of the fine aggregates with recycled concrete fine aggregates, with the addition of silica fume, air-entraining agent, and plasticizer [17], [18].

Steigenberger [19] reported an Austrian highway (A1 near Vorchdorf) where recycled concrete aggregates were used in the bottom concrete layer of the pavement. The pavement consisted of a 50-mm thick exposed aggregate concrete layer overlaying a 210-mm recycled concrete base with NMAS 32 mm. Transverse contraction joints were sawn every 5.5 m. This type of pavement is typically referred to as PCC/PCC composite pavement (where PCC stands for Portland cement concrete).

In Germany, there are numerous sections of recycled concrete pavements along the A93 highway between Brannenburg and Kiefersfelden, a highly trafficked highway serving as the main link between Munich and Innsbruck. The pavement was built between 1995 and 1996. Recycled concrete aggregates were used in the lower concrete pavement layer, which was 190 mm thick. The PCC surface layer was 70-mm thick, incorporating high-quality aggregates. After ten years of intense use, the pavement did not show signs of degradation, despite the very low level of maintenance performed [20].

One of the main differences between the European and the American case studies was that, in Europe, the recycled concrete pavement aggregates were only used in new pavements if there were no signs of durability cracks and alkali-silica reaction (ASR), and the old pavement was in good condition. Durability cracks, also referred to as "D-cracking", are caused by freeze-thaw deterioration of aggregates in the concrete. The American studies, however, indicate that there are mitigation measures available to address issues observed in the original concrete including mitigation of ASR.

The Minnesota Department of Transportation tests [16] showed that D-cracking can be minimized by incorporating fly ash. Pavement sections built with recycled aggregates originating from pavements presenting D-cracking were reported to not present D-cracking after 22 to 26 years [17]. Gress et al. [21] reported another pavement section in Kansas that did not show a recurrence of durability cracks after 9 years.

The risk of ASR can be reduced by the use of pozzolanic materials and cements with blast furnace slag. Gress et al. [21] reported the case of a Wyoming highway where mitigation measures allowed the pavement to perform for 20 years only showing limited evidence of ASR recurrence. It is noted that special attention is required when incorporating recycled aggregates originating from pavements experiencing ASR. Although the risk can be minimized, the problem can still persist.

More recently Rudinicki and Jurczak, in Poland, supported positively the recycling of a high loaded 82 years-old highway (A6), built in 1938 with plain concrete pavement, for the construction of new concrete layers; tests of the fully recycled and crushed old concrete confirmed appropriate results for strength and freeze-thaw resistance requirements, crucial factors for new concrete pavements in the specific climate of the region [22].

3 INVESTIGATION METHODOLOGY

3.1 Concrete pavement removal and crushing

Around 2009, SSMRR slabs from sections presenting vertical movements, pumping (Figure 3), and faulting at the joints were removed. The slabs were initially broken into blocks with a maximum dimension of approximately 500 mm using a hydraulic drill (Figure 4 and Figure 5). The environmental agency issued a requirement for the material to be taken to a crushing plant, where the concrete blocks were processed with a jaw crusher.

Figure 3. Concrete pavement prior to removal.

Figure 4. Broken-up concrete slabs collected from right lane at KM 24 km.

Figure 5. Concrete block with dowel at the crushing plant.

Following primary crushing, dowels, tie bars, and joint sealants were manually removed. The resulting material was sieved and divided into five fractions of different particle sizes, namely bolder, cobble, pebble; granule; and sand (Figure 6). In view of the European and American experiences, the use of recycled concrete fines was actually limited. Details on crushing techniques employed in the preparation of recycled aggregates are presented by Ulsen et al. [23].

Figure 6. Different particle size fractions obtained following primary jaw crushing.

3.2 Original concrete testing

Cylindrical specimens were cored from several removed SSMRR concrete blocks for indirect (splitting) tensile strength and modulus of elasticity testing. The extraction process is illustrated in Figure 7. The cores measured 54 mm in diameter and 100 mm in length.

Figure 7. Extraction of cylindrical cores from the original pavement blocks.

3.3 Laboratory controls and recycled concrete mixing steps

3.3.1 Recycled concrete aggregates characterization

Representative recycled aggregate samples were obtained either by preparing homogenization piles or using a Jones splitter. In the homogenization pile, the material is distributed evenly with buckets in an elongated pile, alternating the direction of pouring. Once all the material is distributed, the ends of the pile are collected and redistributed. The pile is then divided into similar volumetric fractions. The Jones splitter divides the material into two equal parts by a series of shuts that discharge material in opposite directions.

Physical testing performed on the recycled concrete aggregates included particle size distribution sieve analysis, Los Angeles abrasion value, water absorption, density, and porosity. The chemical constituents of the recycled aggregates were determined with an X-ray fluorescence (XRF) spectrometer, using the *Panalytical Magix Pro spectrometer*.

3.3.2 Raw material for the concrete mixtures – new and recycled

3.3.2.1 Concrete mixes

The study included concrete mixes with NMAS 25 mm and 38 mm. Control specimens (C1) were prepared using conventional virgin aggregates. In the recycled concrete specimens, all the coarse aggregate portion was replaced by recycled aggregates. For each NMAS, three different proportions of fine aggregate replacement were adopted, as shown in Table 1.

The virgin coarse aggregate used was a typical crushed granite from the São Paulo Metropolitan Region. The virgin fine aggregates consisted of 25% (by mass) sand quartz from a river quarry and 75% (by mass) industrial sand. The quartz sand had the fineness modulus of 1.262; NMAS 0.6 mm; specific mass of 26.20 kN/m^3, and 1.7% by mass passing the 75-micron sieve. Industrial sand is generated during granite rock crushing at a commercial quarry. The industrial sand used had a fineness modulus of 2.639; NMAS 4.8 mm; specific mass 26.55 kN/m^3, and 16.9% by mass passing the 75-micron sieve. All the material was washed and sieved.

Table 1. Control and recycled concrete mixtures [24].

Mix	Coarse aggregate	Fine aggregate	NMAS (mm)
Reference (C1)	virgin (100%)	virgin (100%)	25
4/25-F1	recycled (100%)	virgin (100%)	25
4/25-F3	recycled (100%)	virgin (50%) + recycled (50%)	25
4/38-F1	recycled (100%)	virgin (100%)	38
4/38-F3	recycled (100%)	virgin (50%) + recycled (50%)	38

3.3.2.2 Cement

The cement used in all mixes was a sulfate resistant Portland cement with 35% grounded blast slag, also called high oven cement. The mortar's compressive strength at 28 days was 40 MPa.

3.3.2.3 Plasticizer

All the mixes included a liquid lignosulfonate-based plasticizer to improve workability. This plasticizer acts reducing water surface tension, improving the dispersion of cement particles in the mix.

3.3.3 Concrete mixtures – proportions and preparing

The concrete mix design followed the procedure proposed by Helene and Terzian [25]. Table 2 shows the mix design proportions.

Table 2. Concrete mix designs [19].

Mix Code	C1 (ref.)	4/25-F1	4/25-F3	4/38-F1	4/38-F3
Cement: sand: coarse agg.	1:1.80:3.12	1:1.80:2.67	1:1.74:2.67	1:1.81:2.68	1:1.75:2.68
Mortar content (%)	47	51	51	51	51
Virgin coarse agg. (kg)	63.53	-	-	-	-
Recycled coarse agg. (kg)	-	59.63	59.63	59.91	59.91
Total fine agg. (kg)	36.74	40.28	38.89	40.28	38.97
Quartz sand (kg)	9.19	10.07	5.04	10.07	5.04
Crushing sand (kg)	27.56	30.21	15.11	30.21	15.11
Recycled (kg)	-	-	18.75	-	18.82
Cement content (kg)	20.36	22.32	22.32	22.32	22.32
Water (kg)	9.92	13.91	14.66	13.16	14.16
Supplementary water (kg)	-	2.75	3.5	2.00	3.00
Plasticizer (mL)	67.85	74.39	74.39	74.39	74.39
Gross w/c	0.49	0.62	0.66	0.59	0.63
Effective w/c	0.49	0.52	0.5	0.47	0.47
Slump (cm)	5.0	4.0	5.0	5.0	5.5
Entrained air (%)	1.40	2.5	2.40	1.70	1.60
Fresh concrete specific mass (kg/m^3)	2.399	2.301	2.265	2.301	2.252
Pondered absorption in 24 hs (%)	0.00	3.20	4.60	3.00	4.30
Cement consumption (kg)	374	358	353	360	352

For the concrete design, concrete mixing involved the following steps:

- Material weighing, separating 500 ml of water for slump correction post-mixing, and 100 ml for washing the beaker used to measure the additive;
- Pre-wetting of the concrete mixer;
- Adding coarse aggregates in ambient moisture condition;

- Adding half of the water and mixing for one minute;
- Adding cement and mixing for one minute;
- Adding fine aggregates in ambient moisture condition, the remainder of the water, the additive, and the 100 ml that was separated to wash the additive beaker; them mixing for three minutes. If necessary, based on visual observation, part of the 500 ml of water reserved for slump correction can start being added;
- Following slump testing, adding water as required to achieve the desired workability.

For the recycled mixes, concrete mixing followed the process proposed by Tam et al. [26], as follows:

- Material weighing, separating the water into two equal parts, and then separating 500 ml of one of the second half for slump correction post-mixing, and 100 ml for washing the beaker used to measure the additive;
- Pre-wetting of the concrete mixer;
- Adding coarse and fine aggregates in ambient moisture condition and mixing for one minute;
- Adding half of the water and mixing for one minute.
- Adding cement and mixing for thirty seconds;
- Adding the second part of water, the additive, and the 100 ml that was separated to wash the additive beaker; them mixing for two minutes;
- Following slump testing, adding water as required to achieve the desired workability.

3.3.4 Mechanical properties of the concrete

Mechanical properties assessed included: third-point load flexural strength or modulus of rupture (flexural strength or modulus of rupture), indirect tensile strength (split test), uniaxial compressive strength, and modulus of elasticity. This last parameter (E) was assessed using four different methodologies: based on strain-gages deformations during flexural and indirect tensile tests; based on Möhr analogy and Linear Variable Differential Transformer (LVDT) measured central beam vertical deflection during flexural tests; and based on LVDT vertical displacements during compressive tests. Except for the method where Möhr analogy was used, the (secant) modulus of elasticity was obtained from stress-strain curves from 5% to 70% of the maximum stress. Complementarily, the dynamic modulus of elasticity was estimated through an ultrasonic pulse velocity tester (PUNDIT).

4 RESULTS

4.1 Original concrete

Table 3 presents the results for indirect tensile strength (ASTM C496-96 [27]) and ultrasonic modulus of elasticity tests. Based on the relationship between indirect tensile strength and flexural strength suggested by Balbo [28], the flexural strength of the original concrete was estimated to be approximately 7 MPa at the age of 8 years. This value, as well as the modulus of elasticity, are typical for conventional concrete pavements, and do not indicate insufficient strength of the original concrete, discarding such hypothesis.

Table 3. Original concrete average parameters (based Tseng [24]).

Sample #	Indirect tensile strength (MPa)	Dynamic modulus of elasticity (GPa)
Number of samples	12	13
Average	5.1	45.4
Standard Deviation	0.7	2.9
Coeff. of Variation (%)	14.3	6.5

4.2 Aggregates characteristics

The concrete blocks were crushed using jaw crushers in a closed circuit in order to achieve aggregates with NMAS of 38 mm and 25 mm. A separate study comparing the properties of aggregates obtained using jaw crushers and impact crushers is presented by Ulsen et al. [23]. Figure 8 shows the recycled aggregates' particle size distribution.

The portion of the particle size distribution curve corresponding to coarse aggregates is similar for both NMAS mixes. The particle size distribution of the fine aggregates is also similar; however, the amount of fine aggregates generated is significantly higher in the production of aggregates with NMAS 25 mm (31.5% by mass) compared to the fines generated in the production of NMAS 38 mm aggregates (18.5% by mass).

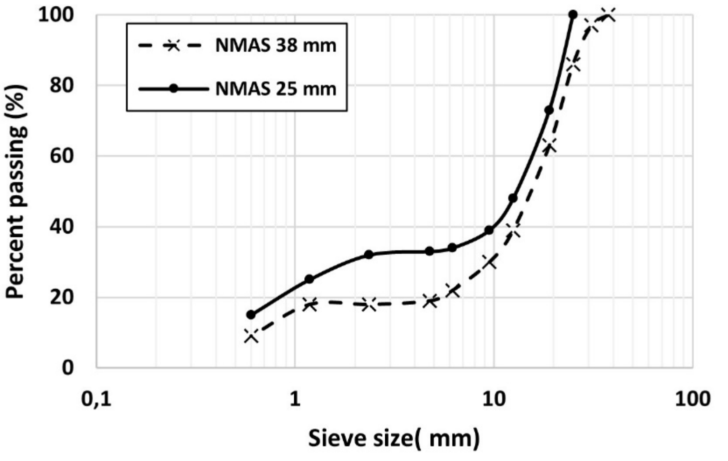

Figure 8. Particle size distribution of the recycled aggregates [24].

4.2.1 Physical characterization

Table 4 summarizes the test results for the physical properties of the recycled aggregates. The coarse aggregates with NMAS 25 mm show higher apparent porosity and water absorption than the coarse aggregates with NMAS 38 mm. The water absorption of the fine aggregates is higher than that of the coarse aggregates, indicating a higher cement paste content in the fine aggregates. The fines generated during the production of NMAS 25 mm presented slightly higher water absorption than the fines generated in the production of NMAS 38 mm aggregate. The Los Angeles abrasion values are within the limits specified for concrete mixes in Brazil (maximum of 50%).

Table 4. Recycled aggregates physical properties [24]

Parameter	Coarse aggregates		Fine aggregates	
NMAS (mm)	25	38	25	38
Apparent specific mass kg/m^3	2.32	2.33	2.47	2.46
Bulk specific mass kg/m^3	-	-	2.70	2.65
Water absorption %	5.39	5.00	6.95	6.71
Apparent porosity %	12.5	11.7	-	-
Particle shape	cubic	cubic	-	-
Los Angeles abrasion value %	32	-	-	-
Paste adhered to aggregate %	29.0	22.3	-	-

4.2.2 Chemical characterization

Table 5 presents the chemical composition of the cement paste obtained from aggregates with different particle sizes, obtained through mass spectrometry. Oxides represent more than 91%. Although the alkali-silica reaction was not evident in the concrete, silica and iron oxides, as well as some small amounts of alkalis (Na and K), were detected. Fluorites were not detected, eliminating the suspicion that the concrete mix had “excessive CaF_2 content”.

Table 5. Chemical composition of the original cement paste [23], [24].

Particle size (mm)	Proportion (% in mass)	Content (% in mass)									
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MnO	MgO	Na_2O	K_2O	TiO_2	P_2O_5
19.1 – 25.4	24.4%	65.2	12.3	3.62	8.52	0.16	1.36	2.12	3.62	0.5	0.18
12.7 – 19.1	35.0%	63.5	12.1	3.97	8.66	0.17	1.35	2.1	3.53	0.49	0.17
6.3 – 12.7	22.2%	63.3	11.2	3.77	9.73	0.18	1.35	1.86	3.35	0.46	0.16
4.8 – 6.3	3.8%	63.1	10.3	3.46	11.1	0.21	1.34	1.6	3.17	0.42	0.14
1.0 – 4.8	8.8%	63.9	9.53	3.25	11.6	0.23	1.29	1.32	3	0.38	0.11
0.15 – 1.0	4.1%	63.2	9.16	3.42	12.4	0.22	1.57	1.1	2.81	0.44	0.1
< 0.15	1.8%	52	10.6	4.39	17.3	0.24	1.98	1.1	2.83	0.61	0.41

4.3 Mechanical properties of recycled concretes

4.3.1 Strength and modulus of elasticity

Mechanical properties assessed included flexural strength [29], compressive strength [30], flexural modulus (obtained using strain gages attached to the bottom of prismatic samples of concretes at 28 days) and modulus of elasticity in compression [31]. The modulus of elasticity (secant) was calculated based on Hooke's law between stresses of 5% and 70% of the ultimate flexural stress. Table 6 presents the results, which were discussed in Balbo et al. [32].

Table 6. Strengths and modulus of elasticity for recycled concretes (based on Steigenberger [19]).

Mix	Age (days)	Number of samples	Flexural strength (MPa)	Flexural modulus of elasticity (MPa)	Number of samples	Compressive strength (MPa)	Compressive modulus of elasticity (MPa)
Control (C1)	7	3	5.3	25	-	-	-
	28	4	5.5	29	3	41.1	23
4/25-F1	7	3	4.9	23	-	-	-
	28	3	5.3	27	4	42.6	21
4/25-F3	7	3	4.7	22	-	-	-
	28	4	4.6	22	4	37.9	22
4/38-F1	7	3	5.1	23	-	-	-
	28	4	5.0	19	5	44.9	23
4/38-F3	7	3	4.5	21	-	-	-
	28	4	4.5	28	6	42.4	22

The mixes containing recycled aggregates presented lower average flexural strength and modulus of elasticity than the control mix. Both flexural and compressive moduli indicate the same trends. The lower strength and modulus values are believed to be related to the higher cement paste content in the recycled concrete mixes. In general, the higher the water absorption, the lower the observed strength and moduli. There were no significant differences in the strengths of the mixes with NMAS 25 mm and 38 mm.

4.3.2 Fracture energy

Later on, three-point bending fracture tests were performed on notched prismatic specimens measuring 100 mm × 100 mm × 400 mm. The notch was 5 mm wide and 25 mm in length. Four specimens of each mix were tested. The span between the two supporting beams was 360 mm. The load was applied at a constant deformation rate of 0.015mm/min. The crack mouth opening displacement (CMOD) was electronically collected at 50 Hz. The duration of each test was 30 minutes. Figure 9 shows the test arrangement according to ASTM C1018-97 [33].

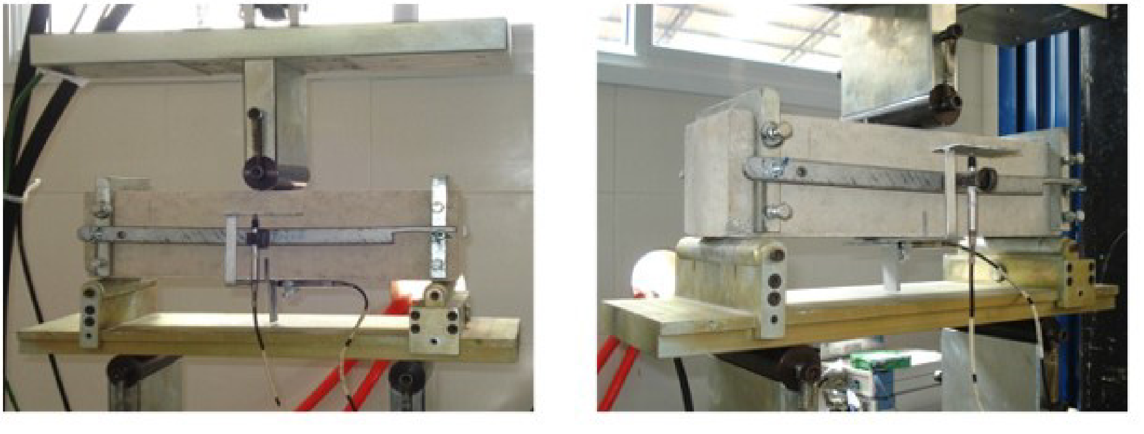

Figure 9. Fracture test arrangement.

Table 7 presents the results for the mixes containing recycled aggregates. For a conventional concrete with flexural strength of 4.5 MPa, Balbo et al. [32] reported a fracture energy of 1,450 N/mm, which is like the values obtained for the mixes containing recycled aggregates.

Table 7. Fracture test results.

Concrete	Parameter	#1	#2	#3	#4	Average	Standard	Coef. of
	Highness to notch (mm)	74.6	75.3	73.7	73.9	-	-	-
	Average width (mm)	100.4	100.4	100.4	100.6	-	-	-
	Load at the LOP (N)	6452	6943	5393	6105	-	-	-
	LOP (MPa)	6.2	6.6	5.3	6.0	6.0	0.5	8.7
4/25-F1	Fissure opening at 1st peak (mm)	0.043	0.019	0.024	0.033	-	-	-
	Area under 0 – 0.10mm (J)	559.3	586.5	445.5	465.1	514.1	69.2	13.5
	Area under 0 – 0.50mm (J)	1237.9	1183.2	1116.5	1145.1	1170.7	52.5	4.5
	Area under 0 – 1.0mm (J)	1442.8	1359.2	1337.3	1290.1	1357.3	63.9	4.7
	Area under 0 – 1.5mm (J)	1514.4	1441.5	1412.9	1337.8	1426.7	73.1	5.1
	Highness to notch (mm)	73.8	74.4	76.6	77.8	-	-	-
	Average width (mm)	100.5	100.8	101.2	100.4	-	-	-
	Load at the LOP (N)	5096	5502	6661	6140	-	-	-
	LOP (MPa)	5.0	5.3	6.0	5.5	5.5	0.4	7.9
4/25-F3	Fissure opening at 1st peak (mm)	0.021	0.0178	0.027	0.029	-	-	-
	Area under 0 – 0.10mm (J)	434.3	444.2	548.5	491.6	479.7	52.3	10.9
	Area under 0 – 0.50mm (J)	1099.4	1069.0	1213.7	1229.8	1152.9	80.6	7.0
	Area under 0 – 1.0mm (J)	1342.2	1252.4	1430.3	1460.0	1371.2	93.7	6.8
	Area under 0 – 1.5mm (J)	1450.6	1318.3	1516.9	1547.1	1458.3	101.6	7.0
	Highness to notch (mm)	73.95	74.06	73.76	74.03	-	-	-
	Average width (mm)	100.8	100.4	100.8	100.8	-	-	-
	Load at the LOP (N)	3604	6178	5946	7229	-	-	-
	LOP (MPa)	3.53	6.06	5.85	7.06	6.32	0.65	10.3
4/38-F1	Fissure opening at 1st peak (mm)	0.088	0.049	0.039	0.053	-	-	-
	Area under 0 – 0.10mm (J)	264.0	485.1	517.8	528.3	510.4	22.5	4.4
	Area under 0 – 0.50mm (J)	1253.0	1300.5	1353.9	1193.3	1282.6	81.8	6.4
	Area under 0 – 1.0mm (J)	1580.6	1457.7	1608.3	1431.7	1499.2	95.4	6.4
	Area under 0 – 1.5mm (J)	1668.5	1486.5	1715.7	1493.5	1565.2	130.4	8.3
	Highness to notch (mm)	74.14	73.74	73.86	74.13			
	Average width (mm)	100.61	101.25	101.20	99.64			
	Load at the LOP (N)	6131	5007	5537	5663			
	LOP (MPa)	5.99	4.91	5.42	5.59	5.47	0.45	8.2
4/38-F3	Fissure opening at 1st peak (mm)	0,030	0,026	0,016	0,298			
	Area under 0 – 0.10mm (J)	493.3	429.4	442.4	474.8	459.9	29.3	6.4
	Area under 0 – 0.50mm (J)	1097.6	1083.6	1093.2	1025.1	1074.9	33.7	3.1
	Area under 0 – 1.0mm (J)	1303.7	1283.9	1253.5	1175.8	1254.2	56.2	4.5
	Area under 0 – 1.5mm (J)	1384.0	1348.2	1301.2	1231.9	1316.3	65.7	5.0

In Figure 10 are shown load *versus* CMOD plots and in Figure 11 are shown fracture energy *versus* CMOD. The R-curve fits presented r^2 minimum of 0.96. Mixes 4/25-F1 and 4/25-F3 presented similar fracture behavior, indicating that replacing 50% of the fine aggregates with recycled aggregates in mix 4/25-F3 did not have a significant effect on fracture behavior. On the other hand, mixes 4/38-F1 and 4/38-F3 presented distinctive behavior. Mix 4/38-F1 resulted in higher fracture energy, suggesting that the combination of larger NMAS and higher recycled fines content was not favorable.

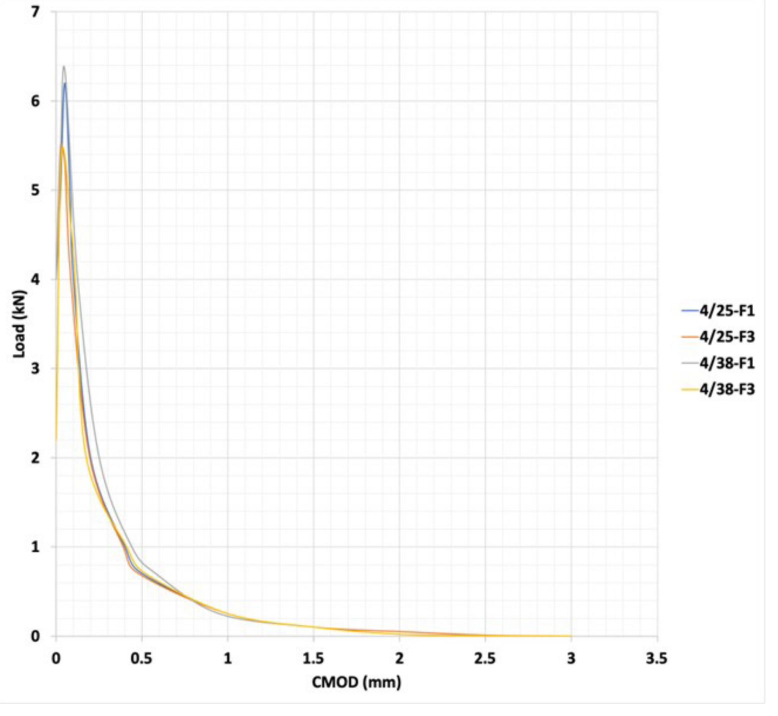

Figure 10. Load versus CMOD.

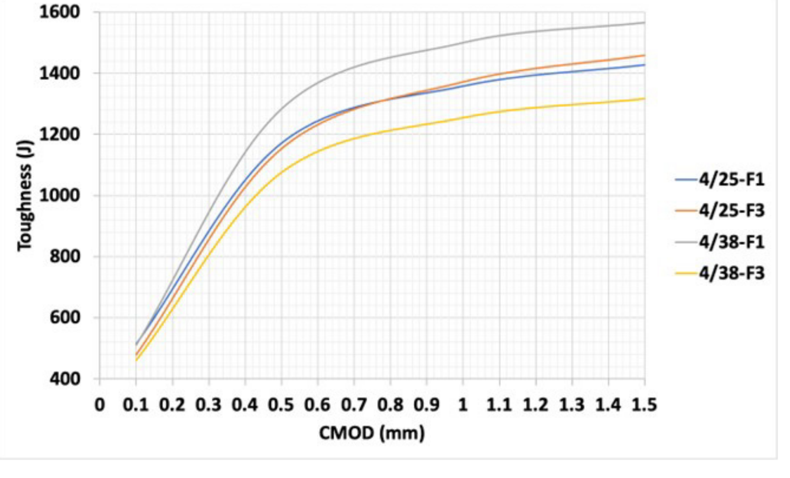

Figure 11. Fracture energy versus CMOD.

4.3.3 Fatigue performance

Fatigue tests were performed at 600 days, with the specimens that were kept in the laboratory at room temperature (arrangements for tests used third point load test principia as required by ASTM C78/C78M-22 [34]). The tests were performed using prismatic samples using a servo-controlled machine at a frequency of 6 Hz (Figure 12).

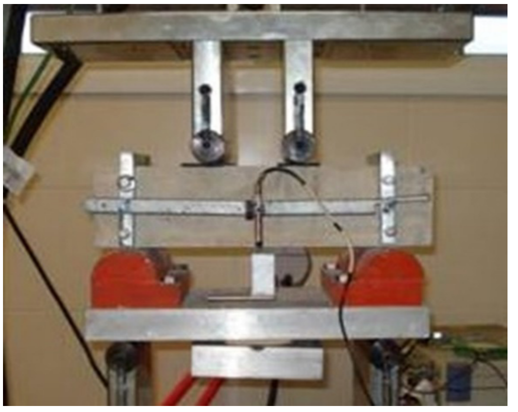

Figure 12. Fatigue test arrangement.

Table 8 summarizes flexural strength test results conducted on samples cured for 600 days, and Table 9 presents the fatigue test results, where the stress-strength ratio (SSR) is the ratio between the applied stress (constant) and the tensile stress in flexural static rupture of the material. The target SSR value was 0.83, which is the value reported by Cervo [35] when testing a conventional concrete comparable to the concrete used at the SSMRR.

Table 8. Physical parameters and indexes for recycled aggregates.

Mix	Samples	Maximum load (N)	Flexural strength (MPa)	Average flexural strength (MPa)
4/25-F1	1	16,799	5.04	5.10
	2	17,228	5.17	
4/25-F3	1	19,127	5.74	5.67
	2	18,691	5.61	
4/38-F1	1	19,189	5.76	5.57 (Sample 3 was eliminated)
	2	19,300	5.79	
	3	17,228	5.17	
4/38-F3	1	16,774	5.03	4.95
	2	16,070	4.82	
	3	16,680	5.00	

Table 9. Results for fatigue tests of recycled concretes.

Mix	Sample	Testing time (s)	Flexural strength (MPa)	Applied stress (MPa)	SSR	N (cycles to fatigue)	log N
4/25-F1	1	4	5.10	4.33	0.85	27	1.43
	2	1,638	5.10	4.33	0.85	9,828	3.99
	3	135	5.10	4.33	0.85	810	2.91
4/25-F3	1	106	5.67	4.82	0.85	636	2.80
	2	1,290	5.67	4.82	0.85	7,740	3.89
	3	12	5.67	4.82	0.85	74	1.87
4/38-F1	1	61	5.78	4.73	0.82	367	2.56
	2	60	5.78	4.73	0.82	361	2.56
	3	86	5.78	4.73	0.82	516	2.71
	4	9,576	5.78	4.73	0.82	57,458	4.76
	5	56	5.78	4.73	0.82	336	2.53
	6	32	5.78	4.73	0.82	191	2.28
	7	4,007	5.78	4.73	0.82	24,042	4.38
	8	48	5.78	4.73	0.82	286	2.46
4/38-F3	1	124	4.95	4.21	0.85	745	2.87
	2	211	4.95	4.21	0.85	1,266	3.10
	3	34	4.95	4.21	0.85	204	2.31
	4	40	4.95	4.21	0.85	243	2.39
	5	152	4.95	4.21	0.85	912	2.96
	6	4,830	4.95	4.21	0.85	28,980	4.46
	7	106	4.95	4.21	0.85	636	2.80

Figure 13 compares the results obtained for the recycled concrete mixes compared to the results obtained for a conventional mix as the original Ring Road mixture [35].

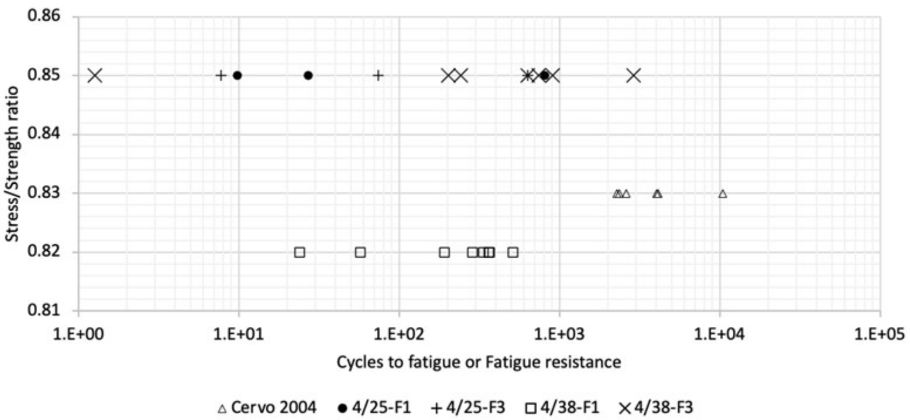

Figure 13. Comparison between fatigue resistances of conventional and recycled pavement concretes.

Based on the limited tests performed, the following was observed:

- NMAS and the percentage of fine aggregates replaced by recycled aggregates did not clearly influence fatigue test results.
- It was not possible to distinguish differences between 4/25-F1, 4/25-F3 and 4/38-F3.
- Mixture 4/38-F1 presented reduced fatigue resistance compared to the conventional mix, even though the SSR was lower. This behavior was not expected since mixture 4/38-F1 did not incorporate recycled fine aggregates.

4.4 Discussion on Structural Durability

As seen the fatigue studies and sample sets were not able for the development of fatigue transfer models to anticipate the number of cycles to fatigue (in cracking) for any stress level. However, a reasonable discussion requires considering, even by simplifying, the available capacity to support moving loads before concrete fatigue consumption. To access some clarification on the matter it was used the standard design criteria for plain jointed concrete pavements of the Brazilian Standardization Association [36]. The design analysis was carried out considering the different recycled concretes fatigue behavior for each fatigue series of tests. Cervo's [35], as pertinent to the concrete employed for the road ring construction, was the reference model for the Brazilian design criteria making reliable the analysis herein presented. The average allowed number of load repetitions for the studied stress levels (SSR in %) for the recycled concretes were then compared to the fatigue model [36], leading to some disclosing conclusions, as follows.

Table 10 presents the allowable number of load repetitions using the fatigue function for the fatigue tested with the recycled concretes: both the average value as well as the individual maximum value found out. This compromise was taken due to the known experience with dynamic fatigue tests and their intrinsically spared results that require tests in three different stress levels (e.g., 85%, 77% and 68%) considering 32 samples for each level. Therefore, the values for averages *Nf* for mixtures 1/24-F1 and 4/24-F3 are small and probably underestimated. Nonetheless, for the maximum *Nf'* values, the fatigue lives of recycled mixtures are under 65% of the reference concrete, a remarkable loss.

Table 10. Allowable number of dynamic load repetitions*.

	fct,f (MPa)	SSR (%)	*Average Nf*	*Nref/Nrecycled* (%)	Max *Nf*	*N'ref/N'recycled* (%)
Cervo [35]; ABNT [36]	5.5	85	30,711	-	30,711	-
		82	174,405	-	174,405	-
4/24-F1	5.3	85	3,555	*11.6*	9,828	*32.0*
4/24-F3	4.6	85	495	*1.6*	774	*2.5*
4/38-F1	5.0	82	10,445	*6.0*	57,458	*32.9*
4/38-F3	4.5	85	986	*3.2*	2,898	*9.4*

*Design parameter: E=30 GPa; k-value of subgrade 40 MPa/m

Under such a perspective it is required, for any design activity, considering the same road traffic for a specified period of design (e.g., 20 years), to compare the slab thickness adjustable for each case, considering the flexural strength (modulus of rupture) of the mixtures. ABNT [36] design guide was employed for this task as follows. The amount of truck road traffic on the original road ring design can be found elsewhere [2]; no growth in traffic was supposed for the analysis. Table 11 presents the required thicknesses for the original concrete and for the alternative recycled concretes, considering the original design truck loads data available publicly. One should note that ABNT [36] design guide performs the verification of accumulated fatigue consumption along the design horizon for both the surface slab and the cemented (RCC) base; therefore, both layers are considered under the verification of Palmgren-Miner fatigue linear damage rule.

Table 11. Slab design for different recycled concretes.

Concrete	fct,f (MPa)	Required thickness for slabs (mm)	FC (%) in 30 years	FC (%) RCC base 30 years	Expectable actual life (years)
Cervo (2004)	5.5	270	3	23	30
4/24-F1	5.3	270	11	23	10
4/24-F3	4.6	300	24	1	1
4/38-F1	5	280	23	2	10
4/38-F3	4.5	300	66	1	3

Based on the *N'ref/N'recycled* verified experimentally for the concretes, it is possible to anticipate the actual expectation of fatigue durability for the recycled pavements as shown in the last column of Table 11 since the designs for ABNT [36] implicitly considers a fatigue model not appropriate for the recycled concretes. Numbers are prone to denote low expectance of life in fatigue for the recycled concretes, what may be considered by designers about where and how to use such alternative material.

5 CONCLUDING REMARKS

This paper discussed the effects of incorporating recycled concrete aggregates on some specific properties of new recycled concretes. The paper focuses on parameters relevant to pavement design and performance. Laboratory test results indicate that higher water absorption leads to lower strength and modulus values. This important aspect requires more investigation in view of the use of high-performance admixtures to improve the strength quality of this new interfacial transition zone (old paste + new paste).

The tensile strength of specimens extracted from the original concrete slabs strength was higher than the design value. Therefore, although the number of tests is small in relation to the number of pavement slabs, its random choice was not prone to prove low resistance as a primary cause of concrete poor performance. Hence, the hypothesis that the pavement underperformed due to insufficient flexural strength was not confirmed.

Chemical spectrometry tests did not detect the presence of calcium fluoride (CaF_2) in the original SSMRR concrete (which is untrue), eliminating concerns related to the presence of harmful chemicals in the recycled concrete aggregates. Therefore, recycling the old concrete slabs for building new pavement slabs or bases, as well as for other civil engineering uses, is not an issue in terms of detrimental chemical reactions.

Recycled concretes were designed to contain 25% or 50% of recycled fine aggregates and recycled coarse aggregates with NMAS 25 mm and 38 mm. All the concrete mixes with recycled aggregates resulted in lower modulus of elasticity, especially the mixes where 50% of fine aggregates were replaced by recycled aggregates. Consideration could be given to the use of a higher cement content or the use of a special emulsified hydraulic binder to mitigate the detrimental effect of recycled aggregates on the modulus of elasticity.

The fracture energy of the recycled concrete mixes was overall similar to that of conventional concrete, except for the mix with NMAS 38 mm and 50% of recycled fine aggregates, which performed less satisfactorily.

The most important conclusion relating to the use of recycled concrete fines is that it not only leads to reductions in static strength, but also in loss of fatigue performance. Considering the same slab thickness, design strength, traffic, and environmental conditions, concrete mixes containing recycled aggregate fines are expected to have a reduced fatigue life. This does not necessarily mean that recycled concrete aggregates should not be used in new concrete pavements, but rather, that the pavement thickness may need to be increased. However, in view of the fatigue design model adopted by ABNT [36], it is clear that life endurance reduction is expected and the best use for the recycled concretes seems to be in pavements with lower traffic volumes than a super-highway as the SSMRR. Based on the cost study developed by Balbo and Dorneles [37], the use of recycled concrete aggregates at the SSMRR would represent a cost increase of 25% to 30% compared to the cost of using virgin aggregates, which corroborates to consider a balance between using green concrete alternative for different and lighter pavements.

Moreover, recycled concrete thicknesses are greater than the originally designed concrete pavement, representing that the volume of concrete removed and crushed, for instance, in 1,000 meters segment, would be enough only for partial pavement replacement, presenting the worst performance (in terms of costs) for the recycled mixtures containing high percentage of recycled fine aggregates. However, the cycle life adjustments based on the comparison of allowed load repetitions of the mixtures containing more fines led to the conclusion they are impracticable, suggesting another civil construction used for the material except for traditional concrete pavement, including concrete and asphalt pavement bases.

Finally, it is important to note that using recycled materials does not necessarily lead to more environmentally sustainable pavements. Sustainability must be assessed by considering the entire life cycle of the pavement, including construction, material transportation, pavement maintenance and rehabilitation activities, user impacts (including rolling resistance and traffic delays) and end-of life impacts (such as material disposal). Therefore, the decision to recycle concrete pavements should not be made solely on the technical feasibility of incorporating recycled aggregates into new concrete mixes, but rather on a holistic assessment taking into consideration all the impacts that such a decision will have over the life of the pavement.

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