Shear strength in the interface between normal concrete and recycled aggregate concrete

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Masters Degree in Civil Engineering

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1. Introduction

1.1. General information

The high exploitation of natural resources associated with the production of concrete is against nature, causing environmental concerns associated with the scarcity of resources and energy consumption. It is necessary to adopt a stance in favour of sustainability and reuse of materials.

In Portugal, the abundance of natural aggregates (NA) allows some lenience towards environmental protection, leading to low levels of recycling rates. Demolition and construction waste (DCW) when landfilled, poses a threat to the environment. However, in the past years changes have been observed, through the Decree-law No. 73/2011 that already prescribes prevention and re-use of waste.

Recycled aggregates from DCW allow a reduction in the exploitation of natural aggregates, protecting and preserving nature. Recycled concrete aggregates (RCA) in particular, have been studied in the past years by various authors, such as Brito (2005) and Etxeberria et al. (2007), relating their properties with the origins, and their incorporation in structural concrete, mechanical performance and durability. In these studies, it was demonstrated that the use of recycled aggregates in concrete could be implemented in the production of concrete.

The effect of concrete incorporating recycled aggregates in shear resistance, within the framework of rehabilitation and strengthening of concrete structures, was never the target of study. However, there are several projects developed on the shear resistance in the interface between normal concretes of different ages, where the influence of roughness, differential rigidity and differential shrinkage is studied. Thus, the main objective of this study is to know the effect of the RCA on the shear resistance and to calibrate the expressions of cohesion and friction coefficient of Santos (2009), depending on the roughness and differential rigidity.

1.2. Scope and methodology of the investigation

The mechanical behaviour and durability of concrete with recycled aggregates and the shear resistance in the interface between different concrete ages depend on the concrete composition and curing conditions. Furthermore, the shear resistance depends on the interface roughness, the differential rigidity and the differential shrinkage. This dissertation aims to study the influence of the shear resistance in the interface between conventional concrete and recycled concrete aggregates concrete, as well as the influence of recycled aggregates on the mechanical behaviour of concrete.

As a first step, a survey was carried out of the national and international literature. The intention was to obtain the maximum information from studies of other authors on the properties of recycled aggregates (RA), the properties of recycled concrete coarse aggregate concrete (RCCAC) and the shear resistance in the interface between conventional concretes.

In another phase, the experimental campaign was prepared and performed. Tests were executed on NA, recycled concrete coarse aggregate (RCCA), concrete in fresh and hardened state and shear between conventional concrete (CC) and RCCAC. In the execution of RCCAC four replacement rates of NA by RCCA were defined: 0%, 20%, 50% and 100%. For the slant shear tests three types of roughness for each replacement rate were performed: cast against wood, steel brush and needle gunned. Slump tests were carried out in all the concrete mixes produced so as to keep the slump in class S3, according to NP EN 206-1. The greater absorption of water by the RCCA was compensated by adding water to the mix. There was no use of superplasticisers or additions. The specimens were kept in a wet chamber during the curing period.

After carrying out the tests, the results were analysed and discussed by comparing them with those collected in the state of the art. The influence of the increased rate of NA replacement by RCCA in all tests performed was determined. In the slant shear test, beyond the analysis of the effect of the replacement rate of NA by RCCA, the effect of the roughness increase and differential stiffness on the shear strength was also analysed. The equations determined by Santos (2009) to calculate the coefficient of friction and cohesion were calibrated so that it was possible to obtain a general expression. While analysing the shear strength, a finite element model was developed, in order to corroborate the effects of differential rigidity and variations of tensions along the surface with the effect of differential rigidity.

2. Experimental descriptions

2.1. Materials

- natural aggregates (NA): sand as natural fine aggregate and gravel as natural coarse aggregate;
- recycled concrete coarse aggregate (RCCA): the recycled aggregate concrete was produced in laboratory, using a concrete jaw crusher; the primary concrete was industrially manufactured and cast ‘in situ’ at the laboratory;
- cement: CEM II 42.5R Portland cement;
- water: tap water was used for mixing and curing.

2.2. Mix design

Four types of concrete mixes were produced, based on the reference mix designed according to the Faury’s method: a reference concrete (NAC), produced with 100% NA, and three recycled aggregate concretes (RAC), with substitution rates of 20%, 50% and 100% of NCA by RCCA (RAC20, RAC50, RAC100). The concrete mixes (NAC and RAC) were prepared with an effective water / cement ratio of 0.52 and a slump of 125 ± 10 mm. None of the mixes was produced with chemical or mineral admixtures. The reference concrete was produced based on the following assumptions and the mix proportions are given in Table 1:

- concrete class: C30/37;
- slump class: S3;
- cement: CEM II 42.5 R Portland;
- maximum particle size: 22.4 mm.

Table 1 - Mix proportions of the reference concrete

Type of aggregate	Size [mm]	Material retained [%]	Volume [m^3/m^3]	Density [kg/m^3]
Coarse aggregate	22.4 - 16	19.3	0.132	351.1
	16 - 11.2	19.1	0.131	348.5
	11.2 - 8	6.6	0.045	119.7
	8 - 5.6	6.5	0.045	119.7
	5.6 - 4	5.7	0.039	103.7
Fine aggregate	Coarse sand	35.1	0.240	500.4
	Fine sand	7.7	0.053	263.9
Cement			0.115	350.0
Water			0.184	183.6
Water / cement ratio			0.52	
Voids			0.017	-
Total			1.000	2340.6

2.3. Testing of aggregates

The particle size analysis was performed according to EN 933-1 (2000) and EN 933-2 (1999). The particle density and water absorption were determined according to NP EN 1097-6 (2003). The bulk density was determined in accordance with EN 1097-3 (2002). The water content was determined according to EN 1097-5 (2011). The index shape was measured following EN 933-4 (2008). The resistance to abrasion was measured by the Los Angeles test according to EN 1097-2 (2010).

2.4. Testing of fresh concrete

The slump and density of fresh concrete was determined immediately after mixing. The slump was measured according to the Abrams' slump test following EN 12350-2 (2009). The density was calculated according to EN 12350-6 (2009).

2.5. Testing of hardened concrete

After the curing period of the samples, the following tests were performed. The 7-, 28-, 56-day compressive strength of concrete was measured according to EN 12390-3 (2009). The 28-day splitting tensile strength was determined according to EN 12390-6 (2009). The elasticity modulus was determined following LNEC E-397 (1993). The abrasion resistance was measured by the Böhme's grinding wheel method according to DIN 52108 (2010). The slant shear test was performed according to EN 12615 (1999).

2.6. Roughness parameters analysis

The roughness parameters analysis was performed according to the 2D laser roughness analyser method (2D-LRA method), developed by Santos and Júlio (2008). The 2D-LRA method consists on the analysis of the concrete surface with a portable laser roughness analyser, with a range of 30-50 mm and a resolution of 10 μm. A linear displacement table allows the laser sensors to perform a maximum evaluation length of 220 mm. Connected to the laser roughness analyser is a laptop with a software developed in National Instruments LabView 7.1, named surfTEX, to control the equipment, assess the data and generate the output text file, containing the coordinates of the texture profile. In Figure 1, the equipment of the 2D-LRA method can be observed.

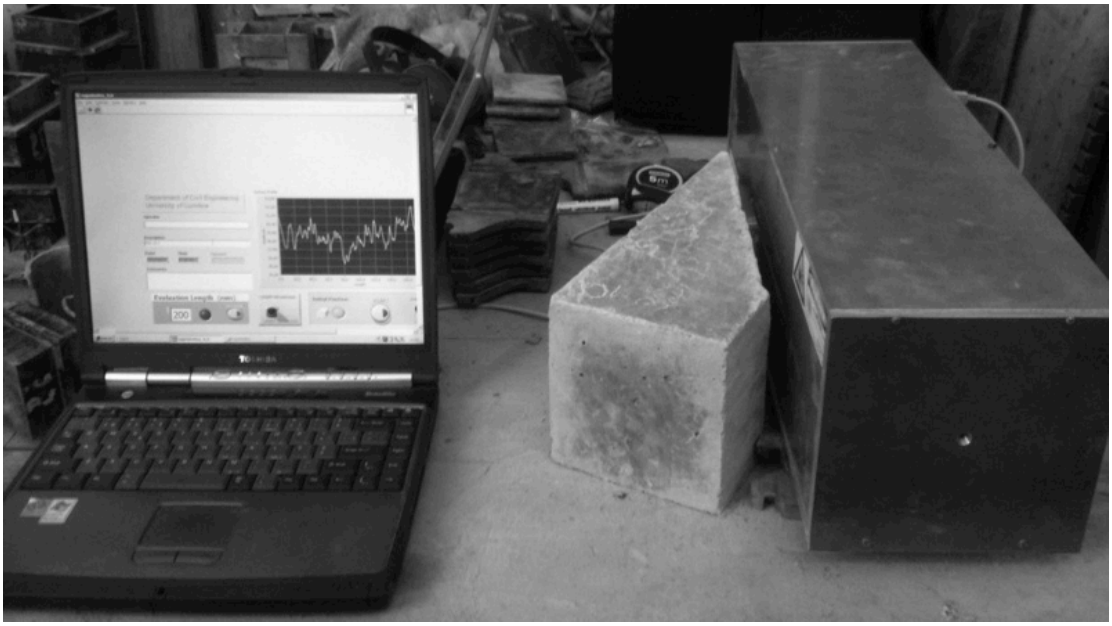

Figure 1 - Equipment of the 2D-LRA method: laptop (left); laser roughness analyser (right)

2.7. Slant shear test

The slant shear test was adopted to assess the bond strength, of the interface between normal concrete and recycled aggregate concrete, with different ages. The adopted geometry for the slant shear specimens was a 150x150x450 mm^3 prism, with the shear plane at 30 degrees with the vertical. For each substitution rate of NCA by RCCA, three types of roughness for the interface surface between the substrate and the added concrete were produced: cast against wood (CAW) as the reference situation; steel brush (SB) treatment; needle gunned (NG) treatment. The interface surface was dried before the casting of the added concrete.

From the roughness analysis the mean valley peak (R_{vm}) was used in order to obtain the cohesion and friction coefficient, as established by Santos (2009), and the roughness and shear strength were correlated. Figure 2 shows the roughness analysis for the three types of interfaces treatments along the interface surface.

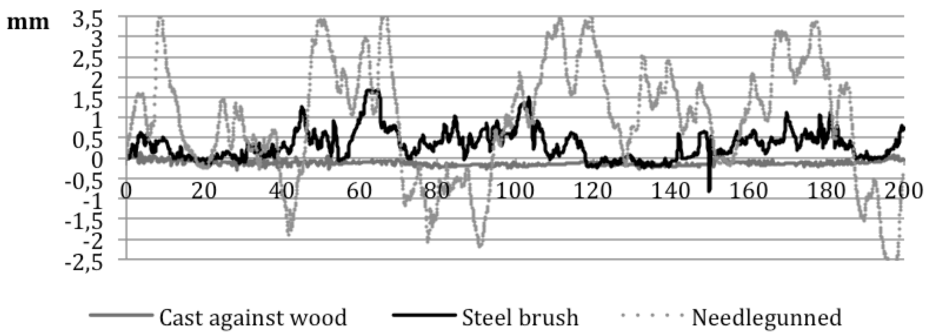

Figure 2 - Roughness analysis along the interface surface

3. Experimental results and discussions

3.1. Aggregates' properties

Table 2 shows the experimental results of the aggregates' tests.

Table 2 - Experimental results of the aggregates' tests

Aggregate	Fine sand	Coarse sand	Natural coarse aggregate	Recycled coarse concrete aggregate
Particle density [kg/m^3]	2619.8	2610.1	2660.0	2230.4
Water absorption [%]	0.31	0.42	0.95	6.57
Bulk density [kg/m^3]	1512.6	1523.1	1325.3	1233.9
Water content [%]	0.1	0.2	1.27	3.42
Index shape [%]	-	-	13.7	22.1
Los Angeles coefficient [%]	-	-	24.6	41.1

The particle density and bulk density of RCCA are considerably lower than those of NCA. On the other hand, the RCCA's water absorption is much higher than that of NCA. The attached mortar in RCCA can explain these results, due to its higher porosity and lower density. Because of the high water absorption of RCCA, the mixing water must be compensated with the estimated quantity of absorbed water of these aggregates during the mixing process.

3.2. Fresh concrete properties

3.2.1. Workability

Table 3 shows the slump results of the characterization concrete (CC) and slant shear test specimens concrete (SSSC).

Table 3 - Slump result of characterization concrete and slant shear test specimens concrete

Concrete	Effective ratio w/c	Slump (CC) [mm]	Slump (SSSC) [mm]
RAC	0.52	120	115
RAC20	0.52	120	120
RAC50	0.52	125	120
RAC100	0.52	130	125

The results show a slight increase of slump with the increase of the substitution rate. However, in both cases the slump was maintained within the stipulated class. The effective water / cement ratio was maintained at 0.52.

3.2.2. Density

Table 4 shows the density results of characterization concrete and slant shear test specimens concrete.

The results show a decrease of density with the increase of the substitution rate due to the lower density of RCCA.

Table 4 - Density results of characterization concrete and slant shear test specimens concrete

Concrete	Density (CC) [kg/m^3]	Density (SSSC) [kg/m^3]
RAC	2370.9	2389.3
RAC20	2340.6	2357.8
RAC50	2315.2	2320.3
RAC100	2244.4	2235.2

3.3. Hardened concrete properties

3.3.1. Compressive strength

Table 5 and 6 shows the 7-, 28- and 56-day compressive strength and 28-day compressive strength of the added concrete of the slant shear test.

Table 5 - Compressive strength after 7, 28 and 56 days of curing

Concrete type	$f_{cm.7}$ [MPa]	Δ [%]	$f_{cm.28}$ [MPa]	Δ [%]	$f_{cm.56}$ [MPa]	Δ [%]
RAC	34.7	-	48.5	-	52.7	-
RAC20	37.2	7.2	49.3	1.6	52.8	0.2
RAC50	36.3	4.6	47.9	-1.2	49.1	-6.8
RAC100	30.4	-12.4	43.4	-10.5	45.7	-13.3

Table 6 - Compressive strength after 28 days of curing, of the added concrete of the slant shear test

Concrete type	$f_{cm.28}$ [MPa]	Δ [%]
RAC-SS	50.0	-
RAC20-SS	47.5	-5.0
RAC50-SS	46.1	-7.8
RAC100-SS	42.7	-14.6

A decrease in the compressive strength values can be observed with the RCCA replacement rates increase in the mixes, for all ages, except for the RAC20 with a small compressive strength increase. A decrease in the compressive strength values for the added concrete of the slant shear test can be observed with the RCCA replacement rates increase. It was expected that compressive strength would decrease linearly with the substitution of NCA by RCCA. However, this was not the case for the characterization concrete. The compressive strength decrease can be explained by the differences between RCA and NA regarding shape, surface texture and resistance. The non-hydrated cement particles adhered to RCCA can explain the RAC20's higher compressive strength.

3.3.2. Splitting tensile strength

Table 7 shows the 28-day splitting tensile strength.

Table 7 - Splitting tensile strength after 28 days of curing

Concrete type	$f_{ctm.28}$ [MPa]	Δ [%]
RAC	3.95	-
RAC20	3.96	0.3
RAC50	3.61	-8.6
RAC100	3.63	-8.1

The 28-day splitting tensile strength exhibits a decrease with the RCCA replacement rates increase, except for RAC20, similarly to compressive strength. The particle shape and surface texture may justify the difference along the RCCA replacement rate. The RAC20 splitting tensile strength increase can be explained by the arrangement of the particles and the non-hydrated cement particles adhered to RCCA.

3.3.3. Elasticity modulus

Table 8 shows the 28-day elasticity modulus.

Table 8 - Elasticity modulus after 28 of curing

Concrete type	$E_{cm.28}$ [MPa]	Δ [%]
RAC	37.6	-
RAC20	37.2	-1.1
RAC50	34.5	-8.2
RAC100	33.0	-12.2

Contrary to what is observed for compressive and splitting tensile strength, the modulus of elasticity shows a monotonic decrease for all the RCCA replacement rates. The elasticity modulus decrease can be explained by the aggregates' origin and consequently, by their different stiffness.

3.3.4. Abrasion resistance

Table 9 shows the 91-day abrasion resistance.

Table 9 - Abrasion resistance after 91 days of curing

Concrete type	ΔL [mm]	Δ [%]
RAC	3.52	-
RAC20	3.52	-0.1
RAC50	2.96	15.93
RAC100	3.67	-4.22

The abrasion resistance does not allow the establishment of a linear relationship with the RCCA replacement rate. Indeed, RAC100 shows the higher abrasion resistance and RAC50 shows the lower abrasion resistance, while the RAC20 abrasion resistance is almost the same as that of RAC.

3.3.5. Slant shear

Table 10 shows the shear strength between the 56-day substrate concrete and the 28-day added concrete.

Table 10 - Shear strength at 28 days of difference between the substrate concrete and the added concrete [MPa]

Bonding type	Treatment		
	CAW	SB	NG
RAC-RAC	6.27	8.59	12.43
RAC- RAC 20	6.11	6.99	13.27
RAC- RAC 50	6.46	6.65	8.43
RAC- RAC 100	4.75	5.76	7.11

The shear strength at 28 days of difference between the substrate concrete and the added concrete has two trends that must be addressed. The first concerns the increase of the interface roughness. This increase due to the different treatments reflects a considerable increase of the shear strength as expected due to the irregularity of the surface, which allows a better connection between the substrate concrete and the added concrete. The second trend concerns the increase of differential stiffness and the use of RCCA. The effect of differential stiffness was studied in the finite element software and represents a significant loss of shear strength. The use of RCCA represents a loss of shear strength due to the loss of stiffness and splitting tensile strength of the concrete caused by them.

From the analysis of Santos' (2009) research on slant shear between normal concretes, performed with a higher concrete strength class, it was observed that concrete strength was an important variable. Further analysis shows that splitting tensile strength was better correlated with shear strength.

From the experimental results of this study and Santos (2009), new equations to calculate the cohesion and friction coefficient were determined:

$$c = 0.1049\, f_{ctm}\, R_{vm}^{0.0179\, f_{ctm}} \left(\frac{E_{c.ad}}{E_{c.sub}}\right) \tag{1}$$

$$\mu = 1.5185\, R_{vm}^{0.0383} \tag{2}$$

The equations optimization was performed with a multi-variable model solving equations, which allowed the best adjustment to the experimental values, calibrating equations 1 and 2 constants and exponents.

4. Numerical modelling

The numerical modelling was performed in Abaqus software. In order to simulate the slant shear test, two parts were defined and assembled in accordance with a linear elastic material behaviour. Boundary conditions were established in order to prevent all displacements in the specimen base and the two horizontal displacements at the top. Bonding surface was determined as a cohesive bonding. Figure 3 shows the parts assembled and the surface definition in Abaqus.

A mesh of 1950 and 2100 plane stress, 8 nodes, isoparametric elements was used for the substrate and the added concrete. This mesh was selected from a set of meshes of increasing number of elements, since the corresponding results did not differ from those obtnained with a more refined mesh.

To evaluate the shear strength a mean line from point A to B of the interface was defined as shown in Figure 4.

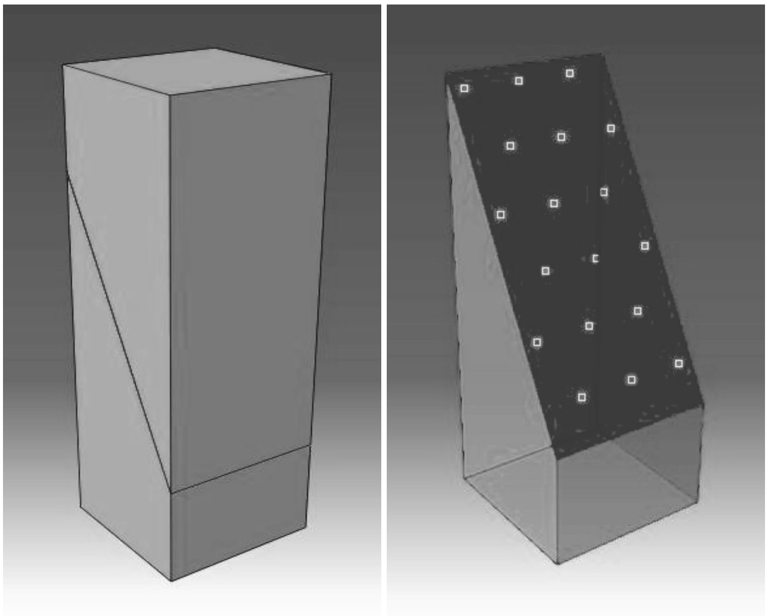

Figure 3 - Parts assembled (left) and surface definition (right)

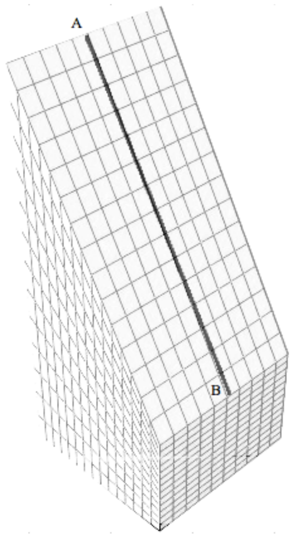

Figure 4 - Mean line of the interface

A 1 mm displacement was imposed to the top of the slant shear specimens for the evaluation of the shear stress in the interface as shown in Figure 5.

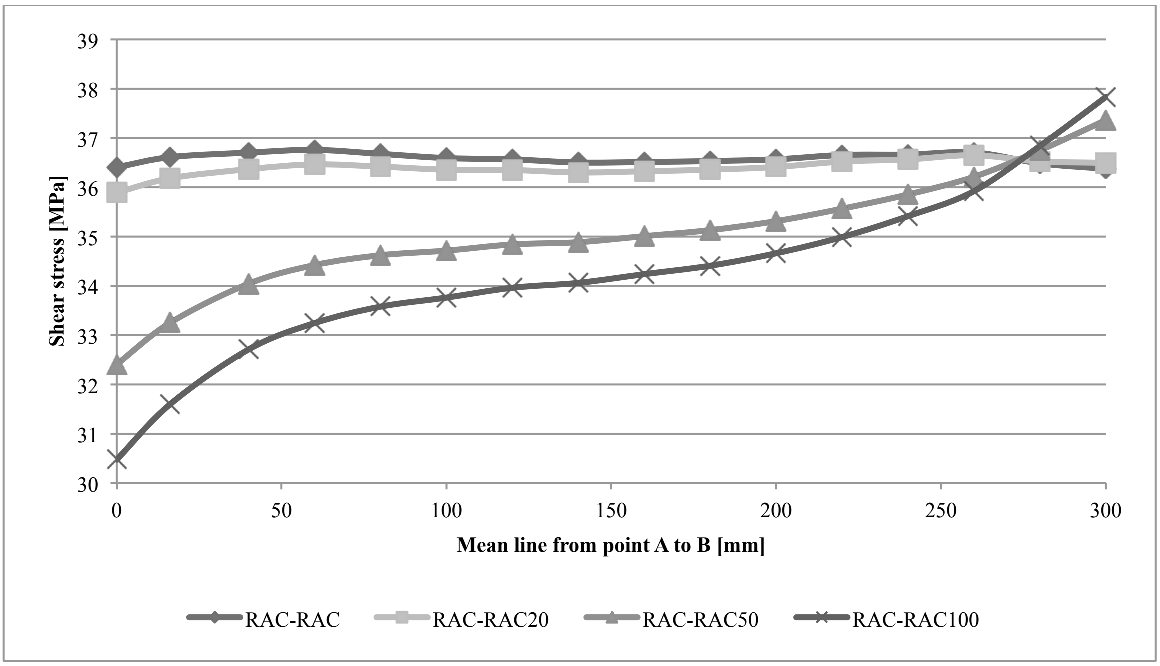

Figure 5 - Evaluation of the shear stress in the interface

Throughout the increase of differential stiffness a shear stress decrease was observed. However, a local increase of shear stress was observed at the end of the mean line. This increase explains some of the specimens ruptures observed. From the results it was concluded that the differential stiffness gives a significant contribution for shear strength.

5. Conclusions

The use of RCCA in RAC must be taken into consideration, in most cases, due to the lower performance when compared to CC. The following conclusions can be drawn taking into account the experimental results:

- Concrete with 20% of RCCA can be used as structural concrete since its properties are similar to those of CC;
- 28-day compressive strength decreases with RCCA incorporation, up to 10.5% in characterization specimens and 14.6% in slant shear specimens;
- Splitting tensile strength decreases with RCCA, up to 8.6% for RAC50;
- Elasticity modulus decreases with RCCA, up to 12.2% for RAC100;
- There is no relationship between the RCCA replacement rate and the abrasion resistance; however, there is an increase in RAC50 of 15.93% and a decrease in RAC100 of 4.22%;
- Shear strength increased with the increase of roughness, up to 137% for steel brush treatment and 217% for needle gunned treatment;
- Shear strength decreased with the RCCA replacement rates, up to 132% for CAW, 149% for SB and 175% for NG; this decrease is related to the RCCAC lesser stiffness when compared with CC; as studied in the finite element model, the differential stiffness has an important influence in shear strength.

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