Layers of recycled concrete aggregates stabilized with cement and coconut fibers

Miguel Ângelo Ramalho Marques, miguel.r.marques@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

The use of compacted granular materials is typical for base layers or sub-base layers of a pavement. One of the problems with using this type of material is that they are natural materials whose exploitation is a cause of concern related to the sustainability of the process. The reuse of construction and demolition waste (CDW) to make those pavement layers is a solution to mitigate the exploitation of natural materials and avoid landfilling for CDW, which can pose environmental problems and is not profitable. The introduction of coconut fiber, which originates from the green coconut husk, a renewable resource that is a waste and is highly available in producing countries at a meager cost, can have beneficial effects such as improving the mechanical behavior of a layer incorporating CDW. In this project, test specimens were produced with CDW and with and without coconut fiber and were subjected to degradation tests with the test being the freeze-thaw test. Results were used to evaluate the durability of the specimens. After using indirect tensile tests to assess the evolution of the strength of samples, it was determined that there is better structural consistency in the mixtures containing coconut fiber. This fact enhances its use to ensure better quality for those types of pavement layers throughout its service life.

Keywords

Aggregate, Construction and Demolition Waste, Limestone, Coconut Fiber, Freezing-and-Thawing, Indirect Traction, Durability.

Introduction

In pavements dimensioned for low to medium traffic, it is common that the base and sub-base layers are normally constituted by granular materials, which, due to their constant need for extraction, becomes an unsustainable environmental problem. A possible solution is the use of construction and demolition waste (CDW) as a partial or total replacement of granular material, with this hypothesis having already been validated by some researchers (Bravo et al. 2015; Bogas et al. 2016; Sadati and Khayat 2016; Prakash Chandar et al. 2018; Tavakoli et al. 2018). The use of CDW as an unbound granular material (UGM) in pavement layers has been analyzed in several studies (Chai et al. 2009; Leite et al. 2011; Gonzalez-Burón and Nougués 2019), where the registered behavior of the CDW is possible to be compared with the natural aggregate (NA). Using CDW brings not only environmental benefits, namely reducing the use of NA and its need for extraction, but also a financial benefit, where the volume of CDW dumped in landfills becomes smaller, considering that its price per ton of deposition has been increasing considerably since the year 2005. There is still some uncertainty in the mechanical behavior and durability of cement-stabilized granular mixtures (CSGM) regarding its flexural strength and fatigue, being the most relevant characteristics in this type of mixture, where fatigue strength is related to cracking in flexible floors. On the durability side, the existing literature is still very limited, being mostly related to traditional tests, such as the freeze-thaw.

The introduction of coconut fiber (CF) as reinforcement in bonded materials have already been analyzed in numerous studies, most of which is related to its use in concrete (Ali et al. 2012, 2013; Ali 2014; Chen and Chouw 2016b; a, 2018; Hwang et al. 2016; Sathiparan et al. 2017; Khan and Ali 2018; Sekar and Kandasamy 2018; Wang and Chouw 2017a; b, 2018). The use of CF as reinforcement had a positive effect on mechanical behavior and durability, particularly on indirect tensile strength, flexural strength, impact strength, and limiting crack development. (Ali et al. 2012; Ali and Chouw 2013; Ramli et al. 2013; Hwang et al. 2016; Sekar and Kandasamy 2018). Sekar and Kandasamy (2018) proved that the length of each CF has a proportional influence on indirect traction tests, in which the greater the length of each one, the greater would have to be the indirect traction force required to cause cracking of the specimen, however, to reduce the processing of the material, no filtering was carried out concerning the length of each CF. The use of high amounts of CF is not recommended as it may negatively affect the workability (Hwang et al. 2016) providing the creation of agglomerates. The higher the percentage by mass of CF used in a mixture, the lower its density will be (Ali and Chouw 2013; Hwang et al. 2016), as the number of voids will be higher, therefore, the correct amount of CF to use it will be optimal when this is sufficient to maintain the structural integrity of the CSGM when a crack occurs, without compromising its workability. Coconut fiber is a material with high lignin content and low cellulose content, slowing its degradation and increasing its durability (Dittenber and Gangarao 2012).

Materials and Test Methods

For the construction of the specimens carried out at IST's laboratory, the RCD used comes from Beja, the NA from the near region of Lisbon while the cement used is the Portland (CEM II, A-L 42,5 R). The CF used would most likely end up in a landfill, so its use as a reinforcement in these mixtures makes it a recyclable material. The properties related to the aggregates used are presented in Figure 1 and Table 1. These are complied with the limits of the Portuguese specification for the aggregate 0/31.5 to be used in CSGM.

In this project, a total of six types of mixtures were produced. Four of them resorted to the use of CDW, which completely replaced the use of natural aggregate. Among these four, two used 2% cement with and without CF, and in the other half, 3% cement, also with and without CF. In the remaining two mixtures, a NA of limestone was used, one of them with the presence of CF so that a comparison could be made to the other mixtures produced. Table 2 presents the characteristics of each mixture as well as the assigned nomenclature.

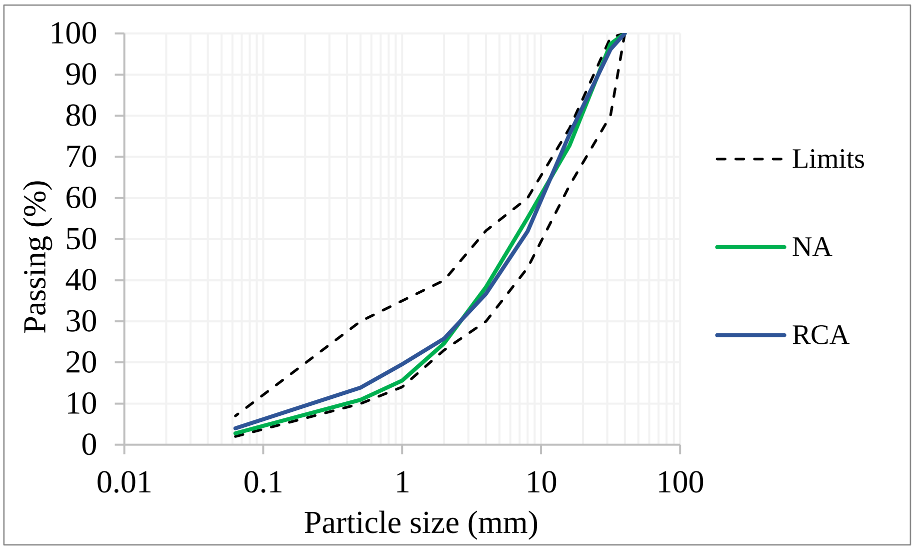

Figure 1 - Grain size distribution of recycled and natural aggregates (adapted from Crucho, 2021)

Table 1 - Properties of the recycled and natural aggregates (adapted from Crucho, 2021)

Property	Standard	Recycled Aggregate	Natural Aggregate	Limit
Fines (% under 0.063 mm)	EN 933-1	4.0	2.8	If fines > 3%, then SE ≥ 50. In case SE < 50, then MB ≤ 2.
Sand equivalent (SE)	EN 933-8	70	39	
Methylene blue (MB)	EN 933-9	7	10	
Flakiness index	EN 933-3	8	11	≤ 30
Shape index	EN 933-4	8	12	-
Los Angeles	EN 1097-2	38	33	≤ 40
Apparent particle density (Mg/m^3)	EN 1097-6	2.75	2.66	-
Particle density on an oven-dried basis (Mg/m^3)		2.42	2.51	-
Particle density on a saturated and surface-dried basis (Mg/m^3)		2.54	2.56	-
Water absorption (%)		4.9	2.3	-

For the construction of the specimens, the ADVAMCE research project was considered in which were used certain characteristics for the specimens so that it was possible to carry out a subsequent comparison of all specimens. The heights, densities, and mass of each specimen were determined before their production, with these values presented in Table 3.

Table 2 - Characteristics of each mixture

Designation	Type of aggregate	Cement Dosage	CF Dosage
CDW_2%	Construction and Demolition Waste	2%	0%
CDW_2%_CF	Construction and Demolition Waste	2%	0.1%
CDW_3%	Construction and Demolition Waste	3%	0%
CDW_3%_CF	Construction and Demolition Waste	3%	0.1%
NA_2%	Natural Aggregate	2%	0%
NA_2%_CF	Natural Aggregate	2%	0.1%

Table 3 - Required properties of the specimens

Intended Height (m)	Intended Density (Kg/m^3)	Diameter of the specimens (m)	Mass (Kg)
0.13	2200	0.151	5.121

The tests carried out during this experiment were the freezing-and-thawing tests and indirect tensile strength tests, according to AASHTO T 136-13 (2015) and EN 13286-42 (2003) standards, respectively. A total of 48 specimens were produced, with 8 specimens for each evaluated mixture. For the first test, two specimens of each mixture were used, the first - type 1 - serving as a control, where the values of volume, water content, and mass will be recorded over 12 cycles, while in the second - type 2 - were the specimen that had been subjected to brushing, where the value of the mass will be recorded before and after each brushing, over 12 cycles as well. Each cycle corresponds to performing at least 24 hours in a freezer, due to weekends and holidays, plus 23 hours on defrosting, leaving 1 hour for measurements and brushing. For the second test, the remaining 6 specimens of each of the mixtures were used, where half performed its entire cure (28 days) in a humid chamber while the other half performed 14 days in a humid chamber and the remaining 14 days in immersion.

Results and Discussion

Figures 2 and 3 present, respectively, the values recorded about the volume of specimens after being removed from the freeze and after the thaw situation. Figure 2 shows that there is no trend about the evolution of the volume over the cycles for any of the mixtures produced, however, it can be stated that the variation in volume is quite constant in general. It is also verified that, for the same mixtures where only the presence of CF is varied, those with fiber have mostly greater volume, although the difference between them is low. Figure 2 shows a value in the mixture CDW_2%_CF that arises from a laboratory error that will not be considered in the analysis of the mixture.

On the other hand, in Figure 3 it is not possible to make any of the previous conclusions as there is a considerable dispersion between the recorded values, existing also a small variation of the volume over the cycles. Figure 3 shows a value in the mixture NA_2%_CF that arises from a laboratory error that will not be considered in the analysis of the mixture.

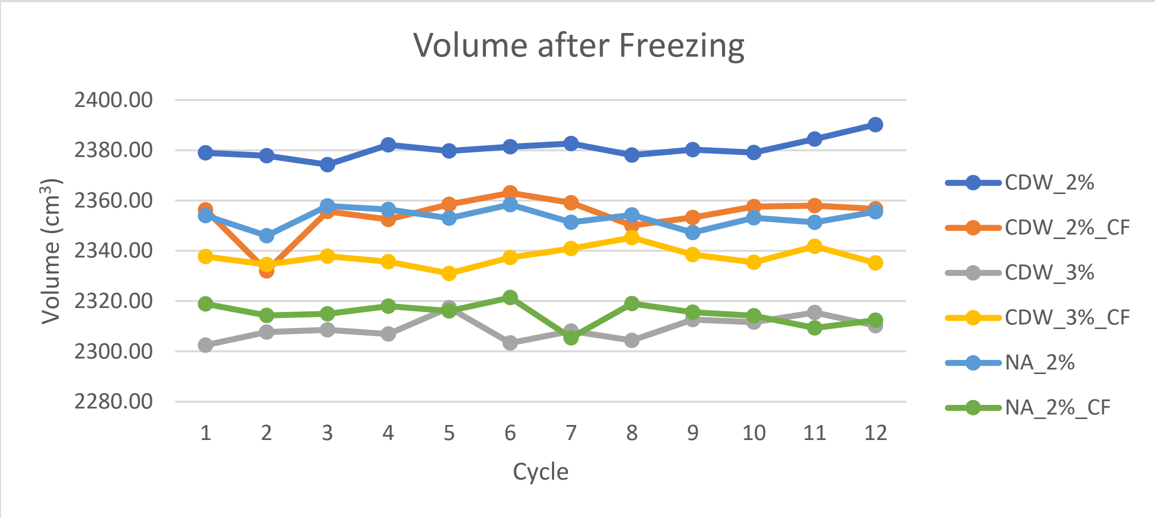

Figure 2 - Volume of the specimens after the freeze situation

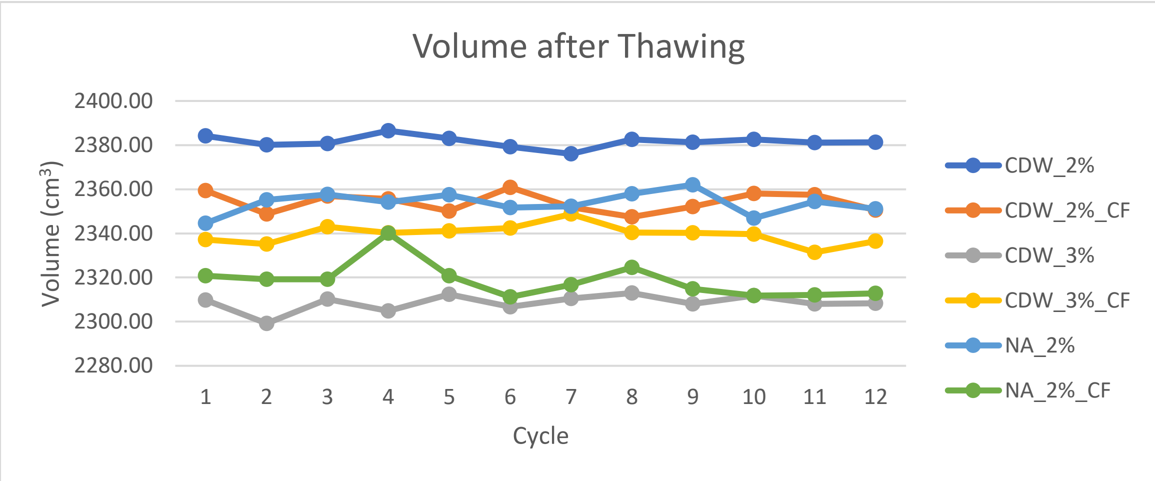

Figure 3 - Volume of the specimens after the thaw situation

About the water content, Figure 4 shows the values collected after the freeze situation and there are mixtures such as CDW_2% and CDW_3% _CF that have an almost constant increase over the 12 cycles, but on the other hand, both NA mixtures have a final water content value lower than the initial and the rest of the mixtures present a constant water content. Figure 4 is also showed a value in mixture NA_2% that comes from a laboratory error and will not be considered.

Figure 5, is presented the values of the water content in the thaw situation, and it's possible to see more clearly the increases registered in Figure 4 for the mixtures CDW_2% and CDW_3% _CF. In the thaw situation, there is much better stability of the values of the water content, but it is still not possible in general to conclude the influence of CF on the water content.

So far, a conclusion that can be drawn based on the observation of volume and water content is that the total replacement of natural aggregate by the recycled aggregate, only increased the water content of the specimens, but in both situations, the behavior turned out to be identical. This higher value was expected as the CDW presents greater water absorption, as shown in Table 1.

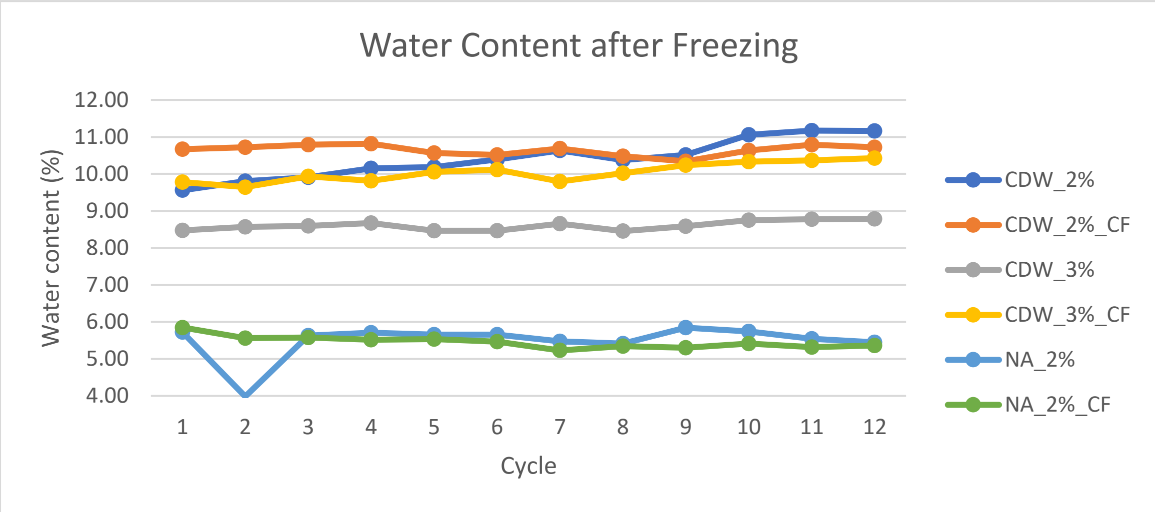

Figure 4- Water content of the specimens after the freeze situation

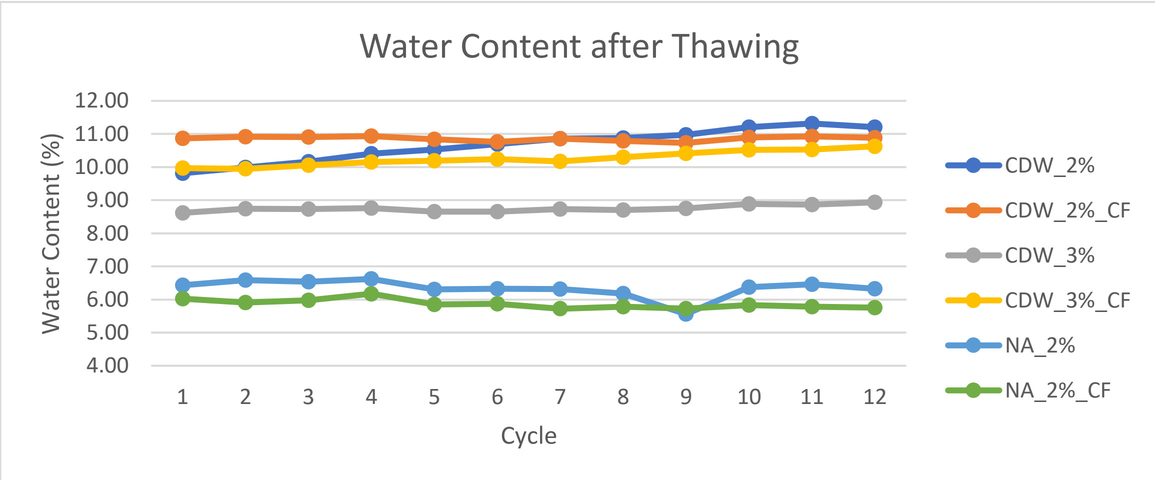

Figure 5- Water content of the specimens after the thaw situation

Regarding the data recorded in type 2 specimens, Table 4 shows the values of the initial mass after its production, the final mass, and the total mass loss over the 12 cycles, where the in this last one, is included the water mass lost and gained by absorption.

It is possible to verify that the specimens with 2% cement without CF are the ones with the greatest loss of material. On the other hand, the specimen CDW_3% was the one with the lowest material loss. With the introduction of CF in specimens, there are some drastic variations in the values of material loss. The specimens with 2% cement with CF, present losses in the same order of magnitude as the specimen CDW_3%_CF. This demonstrates that the CF does show a reinforcing behavior in specimens with smaller amounts of cement, with this trend not being verified in the specimen CDW_3%_CF. It was also verified that the presence of CF contributes to the better structural integrity of the specimen, as it is shown in an example in Figure 6 of the type 2 specimens of NA_2% and NA_2%_CF.

Table 4 - Values of the mass for the type 2 specimens

Designation	Initial mass (g)	Final Mass (g)	Total Loss (g)
CDW_2%	5121.3	4664.9	581.5
CDW_2%_CF	5083.9	4973.6	146.6
CDW_3%	5087.3	5037.2	82.7
CDW_3%_CF	5105.9	5021.6	154.6
NA_2%	5104.6	4641.6	476
NA_2%_CF	5122.5	5032	138.4

Figure 6 - State of specimen NA_2% (left) and state of specimen NA_2%_CF (right)

Regarding the indirect tensile strength tests, the average results regarding the 2% cement CDW mixtures are presented in Figure 7. In this mixture, we can observe that the introduction of CF brought clear improvements to the results obtained. In specimens that have been in a humid chamber for 28 days, the increase in strength is 33% while in specimens that have been in immersion, the increase is only 10%. Another detail observed during the test was the difference in the final state of the specimen after cracking. While specimens without CF broke violently, and it was sometimes difficult to reassemble the specimen, those with CF maintained their structural integrity after breaking, even with a clear cracking. The 3% cement CDW mixtures, shown in Figure 8, this scenario is the opposite of the previous mix. The introduction of CF resulted in worse resistance with the value obtained being 29% lower in the humid situation. In the immersion situation, the average values registered present the same value, with no positive or negative contribution in the use of CF. The strength values of this last mixture are considerably higher than the values from the first mixture in both situations, where the difference between them is the cement dosage. Therefore, the cement has a greater impact on the result of strength than the CF.

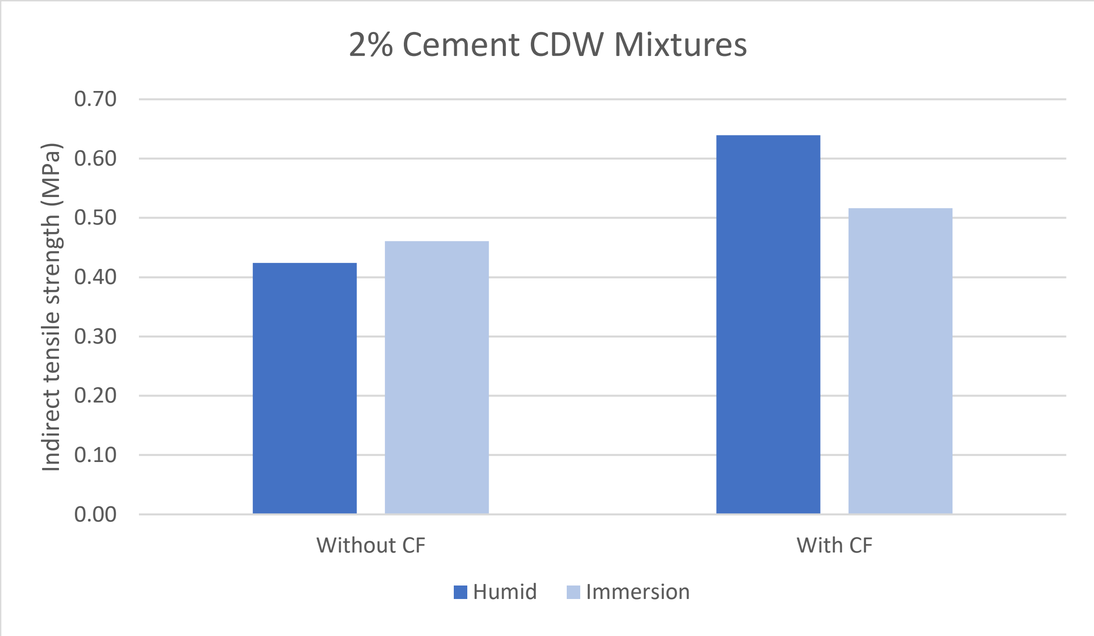

Figure 7 – Average results of the indirect tensile test for the 2% Cement CDW Mixtures

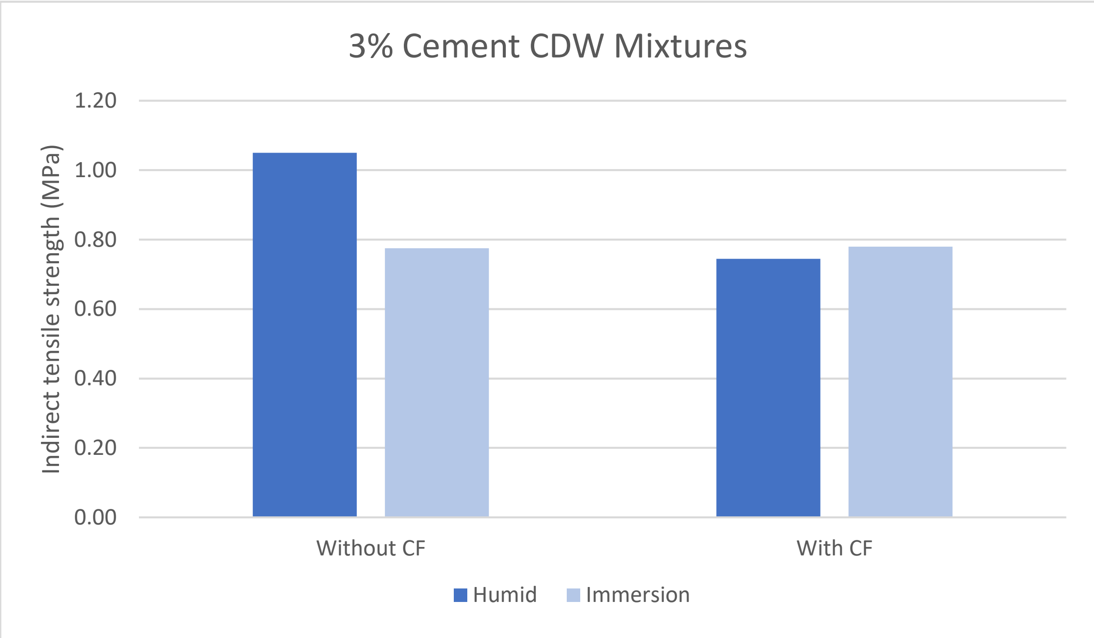

Figure 8 – Average results of the indirect tensile test for the 3% Cement CDW Mixtures

Regarding the mixture of NA_2% with and without CF, shown in Figure 9, the values obtained are closer to those recorded in Figure 7, however, there is also a decrease in resistance. The biggest drop occurred in the immersion situation, where the decrease was 21%. The introduction of CF did not bring any contribution to the registered strength, but there was a clear improvement in the structural integrity of the specimen after the test. Figure 10 is shown a comparison between the final state of specimens without CF (left) and with CF (right) after the indirect tensile test, where the importance of the presence of CF for the structural integrity of the specimen is verified. The CF allowed the splitting to occur as expected but did not allow the complete separation of the specimens, since the CF was tensioned and had sufficient length to keep the two halves together.

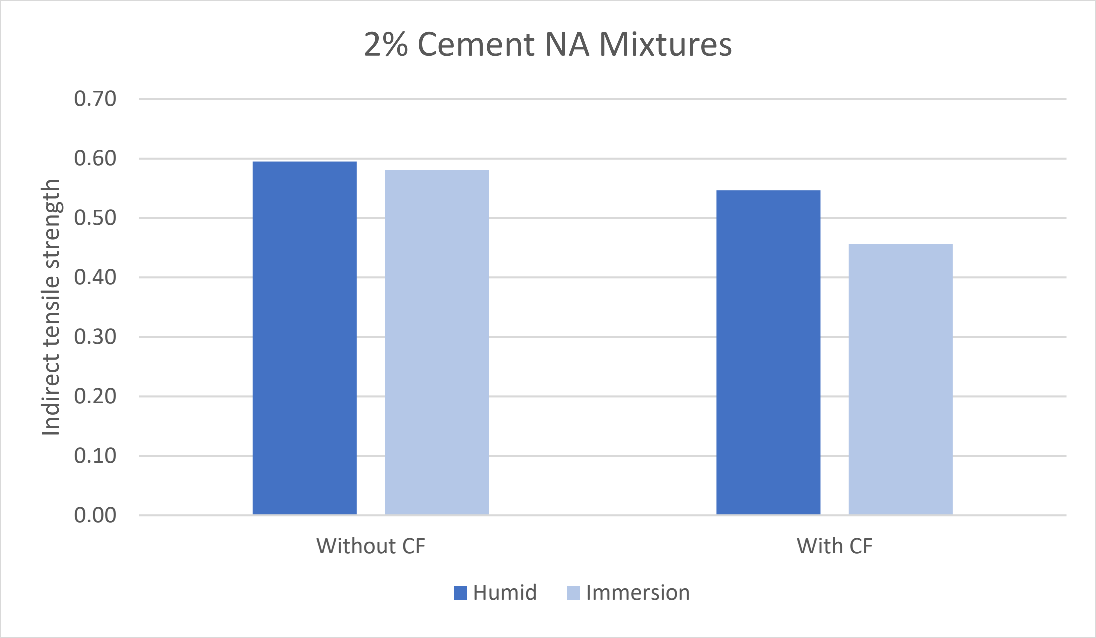

Figure 9 - Average results of the indirect tensile test for the 2% Cement NA Mixtures

Figure 10 - Comparison between the final state of specimens without CF (left) and with CF (right)

In general, no trend in strength values was registered that allows to say that coconut fiber has a clear positive contribution in indirect tensile tests, having only been verified for the RCD mixture with lower cement dosage. On the other hand, it can be safely stated that coconut fiber has a clear reinforcing behavior, not only in the structural integrity of the specimen after its cracking, delaying their increase, but also in its durability.

Conclusions

This article sought to assess the effects that could arise from the total replacement of NA by the recycled aggregate, namely regarding mechanical behavior, and what possible contributions could offer the CF introduced as a reinforcement in the mixtures produced. There were no expected evolution trends in the volume and water content records, possibly due to the variability to which the specimens are subject, which are also not disruptive.

The first conclusion to withdraw is that the use of recycled aggregate in total replacement of natural aggregate did not compromise the mechanical behavior of the specimens. The values obtained in the freeze-thaw tests showed similar values in material loss, with and without CF, when comparing samples with the same cement dosage, varying the type of aggregate. The presence of CF also contributed to the wear occurring only in a superficial way, but a higher dosage of cement also means that the specimen will have better consistency to the brushing.

Regarding the indirect traction tests, the presence of fiber did not prevent a clear cracking of the specimens as expected. However, it allowed this to remain united and consistent when compared to specimens without fiber. From a road point of view, if this solution were applied to a pavement layer for low to medium traffic, the presence of fiber could contribute to better integrity of the layer, potentially delaying an opening of unaffordable dimensions for cracking. With the presence of CF in an aggregate layer stabilized with cement, it was expected to verify a better distribution of the applied load, resulting in improved mechanical behavior and a more adequate response to the degradation mechanisms described in the existing literature, however, the values obtained do not fully verify the veracity of this concept. The use of larger amounts of cement in the mixtures proved to be essential to increase the indirect tensile strength, however, if applied over a considerable extension of the pavement, its financial application may not be viable.

The use of this type of materials contributes to a reduction in the volumes deposited in landfills and will enable savings in the consumption of non-renewable natural resources. In the near future, studies will be carried out on experimental stretches with the materials presented here, allowing a better characterization of the behaviors and a better definition of the potential of using CF in recycled materials for layers sub-base and base of road pavements and in order to improve their performance at controlled costs, contributing to an economy more based on the reuse of by-products in general deposited without reuse.

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