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Article

Translucent Concretes: Comparative Analysis between Sorted and Random Distributions of Polymeric Optical Fibers

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Abstract: This work seeks to approach the comparative analysis of the distribution of POFs (polymeric optical fibers) arranged in a random and sorted manner in the manufacture of translucent concretes. The following characteristics were analyzed: compressive strength, flexural tensile strength, capillary water absorption and light transmittance. Portland cement, water, fine aggregate (sand), silica fume, polycarboxylate ether-based superplasticizer and polymeric optical fiber were used in the production of the composites. Except the fiber content, the mixture of all other inputs was kept as a fixed parameter. Groups with the following levels of POFs were produced: 0%, 2%, 3.5% and 5%. The POF content is the sum of the areas of the fiber sections in the composite with the total area of the translucent surface. The results showed that for the analysis of mechanical behavior (flexural tensile and compressive strength) and durability (capillary water absorption), composites with random and sorted fibers within the 2% POF presented to belong to statistically distinct groups. For the other fiber contents, there was no pattern of behavior, that is, it cannot be said that there is a difference within 3.5% or 5% POF between sorted and random fibers in relation to the mechanical and durability characteristics analyzed. As for the light transmittance, it was attributed that the statistical difference between the fiber arrangements only within the 5% POF content can be a consequence of their accumulation in certain points of the material, thus influencing this characteristic measured by a light meter.

Keywords: translucent concrete; optical fiber; mechanical properties

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1. Introduction

In civil construction, in general, conventional materials that transmit natural light are mainly made of glass, polymers, polycarbonates, among others. Created in 2002 in Hungary, and patented under the name LiTraCon (light-transmitting concrete), translucent concrete is an innovative material that provides a paradigm shift in the use of cement-based matrices [1-3]. Despite the initial denomination LiTraCon or "translucent concrete 'given by the company that originally developed, this consists of a mortar mixture added with fiber not being used, therefore, coarse aggregate [4]. It is believed that this initial choice was motivated by marketing purposes in order to make a bigger impact on the disclosure and popularize this new type of cementitious material. In order to make the nomenclature more appropriate and following the pattern of some international publications [5-7], it was considered more appropriate to use the designation LTCM (Light Transmitting Cement-based Material).

Conventional translucent façades allow light and ultraviolet radiation to enter, providing internal heating for the building [8]. When compared to glass and other conventional materials with similar functions, translucent cementitious materials are innovative and very promising in their use in civil construction [9]. Among the possible practical uses of LTCM´s, the following can be mentioned: traffic signs (eg: translucent speed breakers illuminated from the inside), prison cells (lighting inside the walls, avoiding the possibility of the inmate breaking the lamps and use them as a weapon), external sealing walls in general (aiming to take advantage of sunlight and maintain the thermal inertia of the environment, unlike glass that tends to create a "greenhouse effect"), illuminated public furniture (safer against theft of lamps), fire escape walls, among others.

Translucent cementitious materials have characteristics to improve natural lighting, reducing energy consumption and promoting better conditions of habitability in buildings [10]. Translucent panels have a unique appeal in several aspects, such as improvements in mood, acceptance and visual comfort of the occupants [11]. The use of translucent pieces with a cement base, working as a building envelope, can decrease, for example, some lighting energy that is consumed inside a room or office [12]. Its light transmission properties depend mainly on the amount of inserted optical fiber [13].

Over the past eighteen years, despite LTCMs being widely publicized in the media, in the technical-scientific field they are still underexplored. The possibility of its use for structural purposes as an essential building element, instead of being just a decorative element, requires further research [6]. Confirmation of their structural strength allows sufficient guarantees for this type of use.

This work aims to independently complement previous articles written by these same authors [6,7], making a comparison of LTCM´s samples with POF´s (polymeric optical fibers) distributed in an orderly and random manner according to the following characteristics: compressive strength, flexural tensile strength, capillary water absorption and light transmittance.

2. Materials and Methods

In the experimental program, for each type of fiber arrangement (sorted and random), a reference mortar family was adopted, without the addition of POF, in order to be compared with the other contents. The following tests standardized by ABNT (Brazilian Association of Technical Standards) were carried out: compressive strength, flexural tensile strength, capillary water absorption and light transmittance (the only test proposed which does not exist a Brazilian standard). Figure 1 schematically represents the experimental program divided into four steps.

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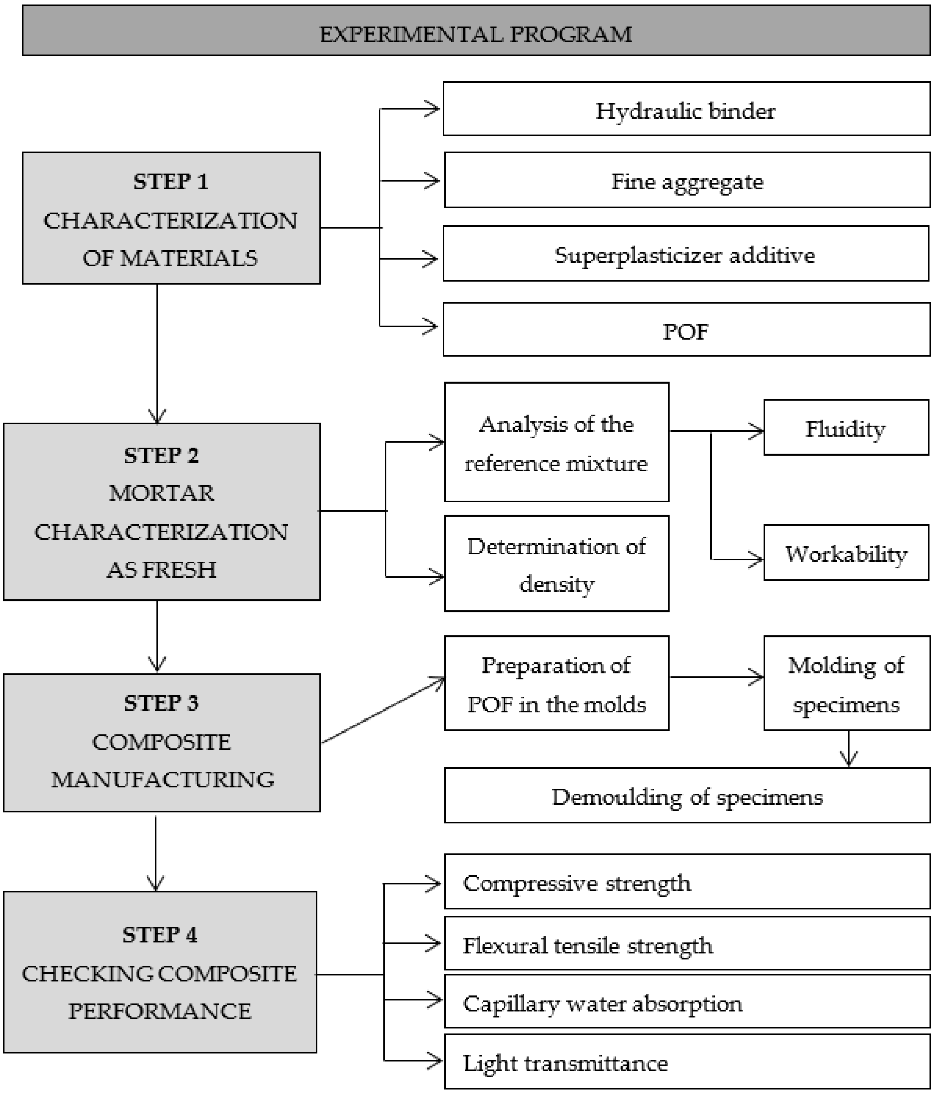

Figure 1. Flowchart of the experimental program.

2.1. Method applied

The specimens with sorted fibers were manufactured in molds with a specific standard size of mortar (4 x 4 x 16 cm) adapted with acrylic plates perforated by laser, as can be seen in Figure 2 a; b. This method allowed to precisely distribute the holes (for the organization and passage of the fibers) in an equidistant way. However, the samples with random fibers were derived from larger monolithic blocks with fibers positioned manually in layers. These, after cutting with a bench saw (Figure 2 c; d), generated specimens with the standardized size, thus allowing the light to conduct through the POFs without the presence of any type of obstruction (cement paste / mortar) at its top ends.

Figure 2. Molding process of translucent concretes: (a) and (b) using technology with sorted fibers; (c) and (d) adopting a method with random fibers [4,7].

To achieve the goals of comparative analysis, four fiber contents were designed: 0%, 2%; 3.5%; 5% POF. These values indicate the relationships between the sum of the areas of the transversal areas of the fibers in the composites and the total areas of the translucent surfaces, as shown in Figure 3. In all specimens, the adopted mixture ratio (except the addition of the optical fibers) was the factor that remained fixed. The performed assessments made in this research sought to study the influence and possible differences in the fiber arrangements in the specimens.

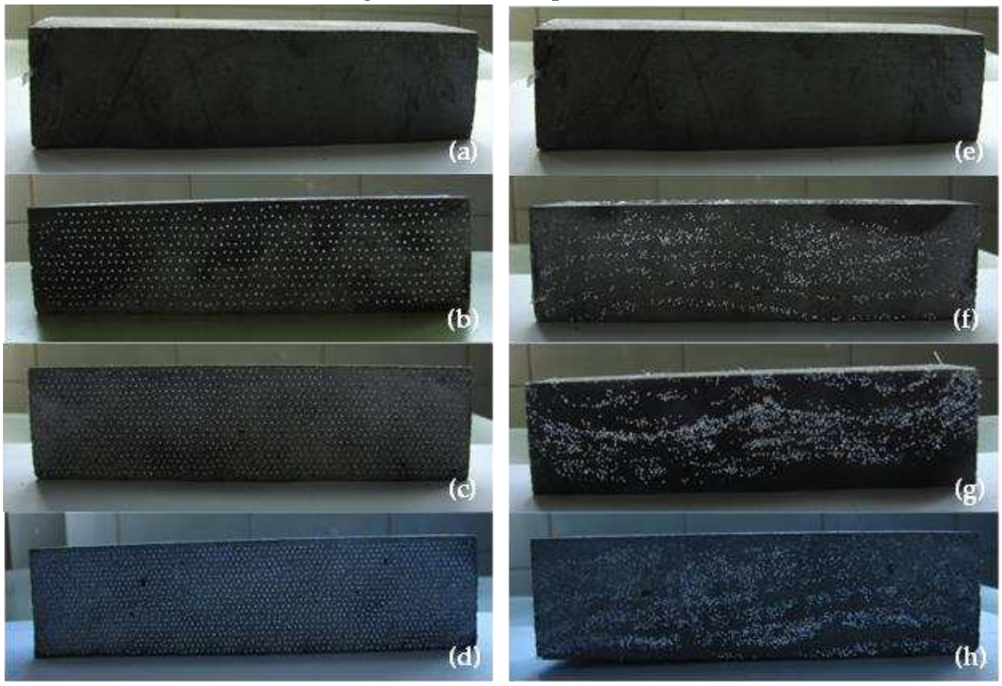

Figure 3. Aesthetic appearance of samples (4 x 4 x 16cm³) disposed in a orderly and random manner with contents of (a) (e) 0%; (b) (f) 2%; (c) (g) 3.5%; (d) (h) 5% POF, respectively [6,7].

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It is important to mention that the reference specimens (0% POF), even without any fibrous reinforcement, were prepared and obtained in the same way as their fiber pairs, as already shown in Figure 2. Thus, the standard for statistical analysis was maintained between the two methods of manufacture.

2.2. Materials used in the study

The translucent concrete samples were produced using Portland cement, water, a fine aggregate (sand), a polycarboxylate ether-based superplasticizer, polymeric optical fibers, and silica fume. The materials are briefly described below, and more detailed information can be found in the literature [6].

CP V ARI type cement was chosen (it is equivalent to Portland cement with a high early strength III - ASTM C150). According to Recena [14], due to its manufacturing process, this type of binder tends to present greater homogeneity in its characteristics. The fine aggregate has its origin in the direct dredging of the bed of the Jacuí river, in Rio Grande do Sul. A polycarboxylate ether-based superplasticizer (PCE) was added to the mixtures to act as a dispersant of the cementitious material and to provide high water reduction. The ratio of this material to the cement mass was 1.0%. A percentage of 10% silica fume, replacing part of the mass of cement, was used to improve the performance (to reduce the permeability, to increase the cohesion and to avoid segregation, among other reasons) of the material. The optical fiber was imported from China.

The surface characterization of the fibers was the first step in the manufacture of translucent composites. Through superficial analyzes, the exact POF amounts for each content adopted were established. It was verified that they presented a very smooth surface with almost no manufacturing defect, such as, for example, microcracks, diameter variation for the same fiber, roughness, among others. The absence of manufacturing defects may be indicative of fiber with good quality and low transmission loss. The verification of the diameter of the POF was of great importance, because through this information the amounts of fibers were calculated for each of the three levels adopted in the specimens. This presented an average size of 0.4 mm (400μm).

2.3. Direction of applied load

As the samples have fibers arranged parallel to each other in a random and orderly manner, in the tests of compressive and flexural tensile strength, it was sought to create a hypothetical situation of application of the translucent plates in order to simulate in the hydraulic press the behavior of use of the material. Assuming the use of translucent concrete as walls, in the compressive strength test, the loads were applied perpendicularly to the fibers in order to try to simulate the very force of the blocks on each other. Likewise, the flexural tensile tests were also simulated for the case of blocks forming a vertical surface. As walls eventually tend to receive accidental loads in the horizontal direction (impacts) or even buckling (if very slender), the flexural tensile tests were performed by applying the load parallel to the direction of the fibers. In Figure 4, a scheme was made showing the direction of the load applied in relation to the fiber layout was the same for both type of samples (with sorted fibers, as well as random ones).

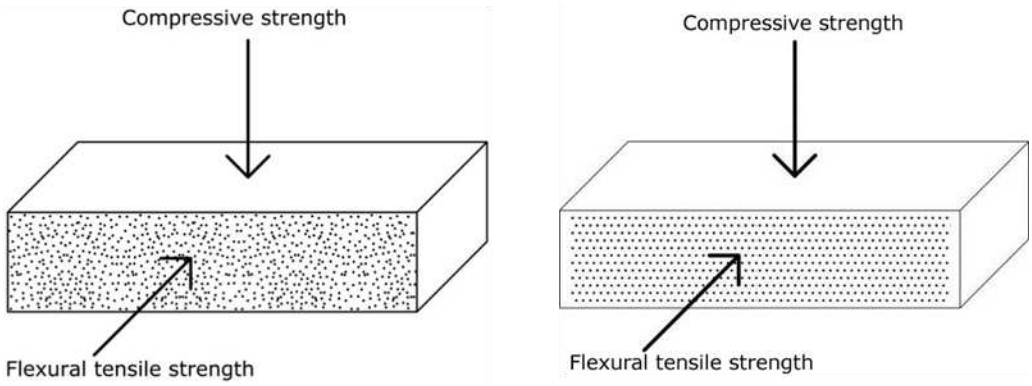

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Figure 4. Scheme showing the direction of the applied loads on the specimens with: (a) sorted fibers; (b) random fibers [6; 7].

2.4. Light transmittance test

For the light transmittance test, a wooden device was built, based on the work published by Uribe [15]. This aimed to evaluate the light transmittance made by the specimens through the different levels of POFs used. In Figure 5, it can be seen that the equipment designed has a hole in its top for fixing a light source (100Watt / 110Voltz lamp), the intermediate part has a support with a rectangular opening (for placing the prismatic samples 4x4x16cm) and the lower part is reserved for the photocell of the luximeter (device used for the measurement of light transmittance). The box was made with naval plywood and was later painted with matte black gouache paint.

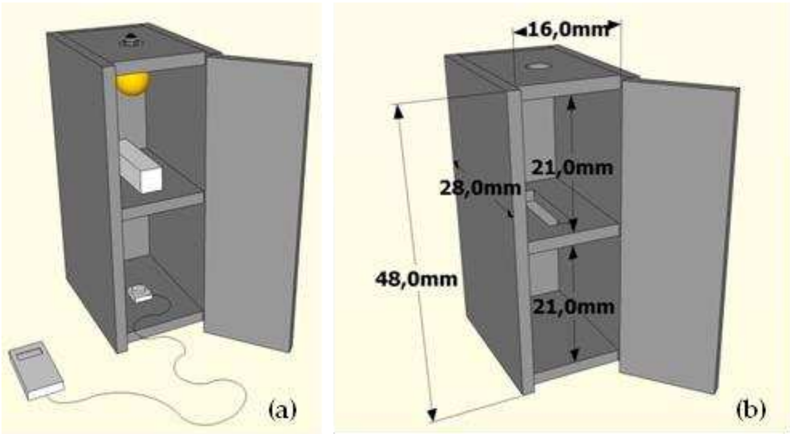

Figure 5. Equipment designed to measure the transmittance of light: (a) device with a light source, specimen and light meter; (b) prescribed dimensions [7].

3. Results

The obtained results from the mechanical properties (flexural tensile and compressive strength), durability (water absorption) and light transmittance are presented in the form of tables and graphs, as well as an analysis of the influence of the studied variables. An important detail to be reinforced is that the numerical difference between the averages of the results for 0% POF families (both with sorted and random fibers) is due to the fact that, despite using exactly the same mixture of mortar, their executions took place differently, as already explained in the methodology. At the end of the discussion of each type of test is a summary of the significant factors obtained through analysis of variance (ANOVA).

ANOVA tests the significance of the difference between the average values of the groups based on the ratio of the variability of the means between groups and the variability of the observations within groups. In this research, all the hypotheses are tested to a confidence level of 95%; that is, there is a probability of error of 5%.

3.1. Compressive strength results

The average results of the standard deviation and coefficient of variation for the compressive strength tests, performed according to ABNT NBR 13279 [16] on day 28, are shown in Table 1. The total number of specimens used to calculate the average results were 36, that is: 16 (4 for each POF content) for the sorted fiber technology and 20 (5 for each POF content) for the random arrangement .It is observed that as POF´s are inserted, both in orderly and random manner, samples tend to have their compressive strength reduced.

Table 1. Average results of the compressive strength tests on day 28.

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Arrangement of fibers	Fiber content (%)	Average compressive strengh (MPa)	Standard deviation	Coefficient of variation (%)
Sorted	0	56.81	1.17	2.06
	2	57.06	1.53	2.68
	3.5	53.99	1.96	3.62
	5	50.64	2.80	5.52
Random	0	59.90	2.13	3.56
	2	53.06	2.09	3.93
	3.5	50.96	3.28	6.44
	5	47.99	1.53	3.19

In Table 2, it is possible to verify, through analysis of variance (ANOVA), that both the fiber content and its arrangements and the interaction of these two variables are statistically significant. Figure 6 shows the graph with the independent statistical study (Duncan's method) for each of the four fiber contents adopted (0%; 2%; 3.5% and 5% POF), comparing the two types of arrangements. According to this, for the same amount of fibrous reinforcement, there is a significant difference only for the 2% POF content between sorted and random manners. This is an interesting indicator for large-scale manufacturing, since translucent composites with sorted fibers tend to have a higher production cost compared to those with random fibers.

Table 2. ANOVA of the compressive strength of the specimens on day 28.

SOURCE	SS	DF	MS	F	Probability	Comment
A: Fiber content	423,847	3	141,282	26,46	0,00%	S
B: Arrangement of fibers	23,995	1	23,995	4,49	4,30%	S
AB	68,564	3	22,855	4,28	1,32%	S
Error	149,526	28	5,340			
TOTAL		35				

SS, sum of squares; **DF**, degrees of freedom; **MF**, mean sum of squares; **F**, test statistic; **Probability** F value, significance level of 5% (Fischer distribution); **Comment** S, significant effect and NS, non-significant effect.

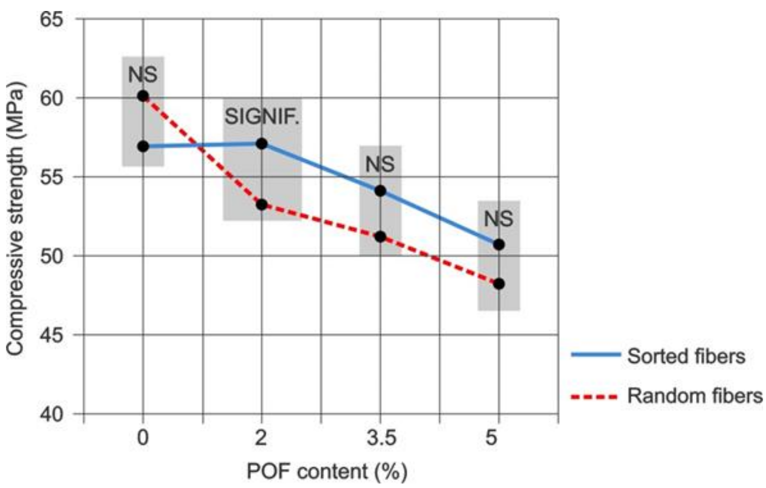

Figure 6. Average results of the compressive strength tests on day 28 and the statistical analysis results via Duncan´ s method.

3.2. Flexural tensile strength results

The average results of the standard deviation and coefficient of variation for the for the flexural tensile strength tests, performed according to ABNT NBR 13279 [16] on day 28, are shown in Table 3. The total number of specimens used to calculate the average results were 36, that is: 16 (4 for each POF content) for the sorted fiber technology and 20 (5 for each POF content) for the random

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arrangement .It possible to say that as the POFs are inserted, both in sorted and randomly manners, the samples tend to have their flexural tensile strength decreased.

Table 3. Average results of the tensile strength tests on day 28.

Arrangement of fibers	Fiber content (%)	Average flexural tensile strength (MPa)	Standard deviation	Coefficient of variation (%)
Sorted	0	1.59	0.19	12.19
	2	1.30	0.07	5.73
	3.5	1.27	0.09	7.51
	5	1.30	0.05	3.88
Random	0	1.89	0.11	6.07
	2	1.50	0.18	11.67
	3.5	1.29	0.07	5.18
	5	1.41	0.16	11.44

In Table 4 it is possible to verify, through analysis of variance (ANOVA), that both the fiber content and the arrangement of these are statistically significant, however the same does not occur for the interaction of these two variables. Figure 7 shows the graph with the independent statistical study (Duncan's method) for each of the four fiber contents adopted (0%; 2%; 3.5% and 5% POF), comparing the two types of arrangements. For families with fibers effectively used, a significant difference was found between sorted and random manners only for the 2% POF. For higher levels (3.5% and 5% POFs), no statistical difference was found between the technologies within the same content. As in the reference samples (0% POF) there is no addition of fibers and the mixture of the mortar is exactly the same, this behavior was attributed to uncontrollable experimental factor (s), possibly related to the molding step (just as occurred in the compressive strength averages) - a subject discussed in the conclusions.

Table 4. ANOVA of the flexural tensile strength of the specimens on day 28.

SOURCE	SS	DF	MS	F	Probability	Comment
A: Fiber content	1.183	3	0.394	21.42	0.00%	S
B: Arrangement of fibers	0.227	1	0.227	12.35	0.15%	S
AB	0.096	3	0.032	1.74	18.18%	NS
Error	0.515	28	0.018			
TOTAL		35				

SS, sum of squares; **DF**, degrees of freedom; **MF**, mean sum of squares; **F**, test statistic; **Probability** F value, significance level of 5% (Fischer distribution); **Comment** S, significant effect and NS, non-significant effect.

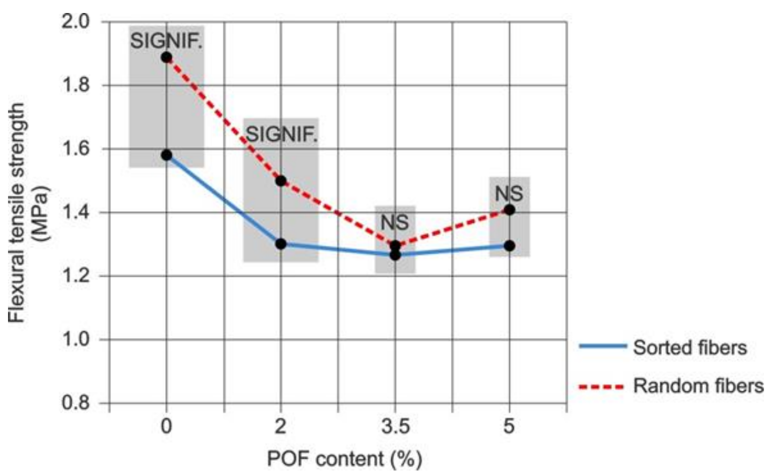

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Figure 7. Average results of the flexural tensile strength tests on day 28 and the statistical analysis results via Duncan´ s method.

3.3. Capillary water absorption results

The average results of the standard deviation and coefficient of variation for the capillary water absorption tests, performed according to ABNT NBR 15259 [17] on day 28, are shown in Table 5. The total number of specimens used to calculate the average results were 36, that is: 16 (4 for each POF content) for the sorted fiber technology and 20 (5 for each POF content) for the random arrangement. It can be seen that the capillary water absorption is increased according to the higher content POF both fiber arrangements.

Table 5. Average results of the capillary water absorption tests on day 28.

Arrangement of fibers	Fiber content (%)	Average capillary water absorption (MPa)	Standard deviation	Coefficient of variation (%)
Sorted	0	0.015	0.005	33.33
	2	0.030	0.016	52.70
	3.5	0.065	0.011	17.20
	5	0.077	0.019	24.78
Random	0	0.022	0.016	74.69
	2	0.068	0.032	46.97
	3.5	0.076	0.039	51.47
	5	0.088	0.024	27.13

In Table 6, it is possible to verify, through analysis of variance (ANOVA), that both the fiber content and the arrangement are statistically significant, however the same does not occur for the interaction of these two variables. Figure 8 shows the graph with the independent statistical study (Duncan's method) for each of the four fiber contents adopted (0%; 2%; 3.5% and 5% POF), comparing the two types of arrangement of the fibers. The greater the fiber content, the greater the water absorption. Specimens with random fibers have a higher capillary water absorption than those with sorted, but only for the 2% content the difference is statistically significant between the technologies.

Table 6. ANOVA of the capillary water absorption of the specimens on day 28.

SOURCE	SS	DF	MS	F	Probability	Comment
A: Fiber content	0.021	3	0.007	12.00	0.00%	S
B: Arrangement of fibers	0.002	1	0.002	4.14	5.16%	S
AB	0.001	3	0.000	0.77	51.98%	NS
Error	0.017	28	0.001			
TOTAL		35				

SS, sum of squares; **DF**, degrees of freedom; **MF**, mean sum of squares; **F**, test statistic; **Probability** F value, significance level of 5% (Fischer distribution); **Comment** S, significant effect and NS, non-significant effect.

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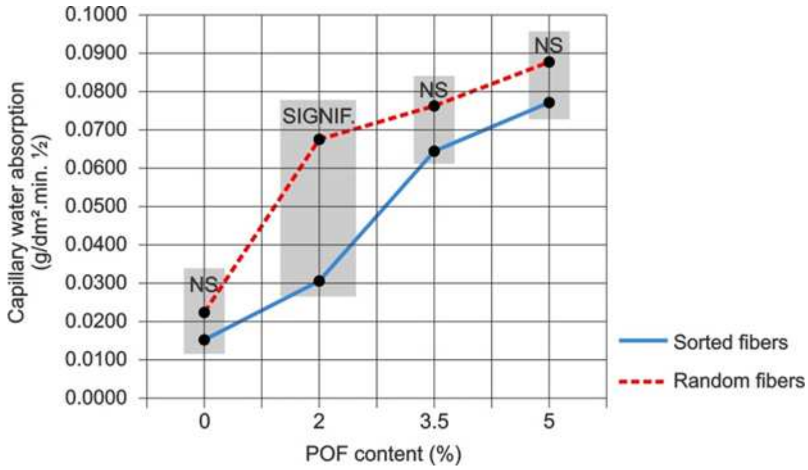

Figure 8. Average results of the capillary water absorption tests on day 28 and the statistical analysis results via Duncan´ s method.

3.4. Light transmittance results

The average results of the standard deviation and coefficient of variation for the light transmittance tests, are shown in Table 7. The total number of specimens used to calculate the average results were 36, that is: 16 (4 for each POF content) for the sorted fiber technology and 20 (5 for each POF content) for the random arrangement.

Table 7. Average results of the light transmittance tests on day 28.

Arrangement of fibers	Fiber content (%)	Average transmittance of light (lux)	Standard deviation	Coefficient of variation (%)
Sorted	0	0	-	-
	2	7.67	0.58	7.53
	3.5	11.33	0.58	5.09
	5	25.00	1.00	4.00
Random	0	0	-	-
	2	7.67	0.58	7.53
	3.5	11.67	0.58	4.95
	5	23.33	1.15	4.95

The data obtained from light transmittance for the 0% POF belonged to the specimens without the addition of POF. In this content, the sealing efficiency of the apparatus developed in the research was tested (Figure 5). As the results for 0% POF showed 0 lux transmittance, confirmation of its light-sealing accuracy was obtained. Through Table 7, it can be seen that as fibers are increased, both in sorted and random manners, as already assumed, they gradually increased the light transmittance. In Table 8, it is possible to verify, through analysis of variance (ANOVA), that only the fiber content is statistically significant, that is, their arrangement does not significantly influence light transmittance. In Figure 9, observing the graph with the independent statistical study (Duncan's method) for each of the four fiber contents adopted (0%; 2%; 3.5% and 5% POF), it appears that the higher the fiber content in the samples, the higher the transmittance. Only for the 5% POF content there is a statistically significant difference between the sorted and random fibers.

Table 8. ANOVA of the light transmittance of the specimens.

SOURCE	SS	DF	MS	F	Probability	Comment
A: Fiber content	1833,667	3	611,222	1333,58	0,00%	S
B: Arrangement of fibers	0,667	1	0,667	1,45	24,53%	NS

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AB	3,667	3	1,222	2,67	8,29%	NS
Error	7,333	16	0,458			
TOTAL		35				

SS, sum of squares; **DF**, degrees of freedom; **MF**, mean sum of squares; **F**, test statistic; **Probability** F value, significance level of 5% (Fischer distribution); **Comment** S, significant effect and NS, non-significant effect.

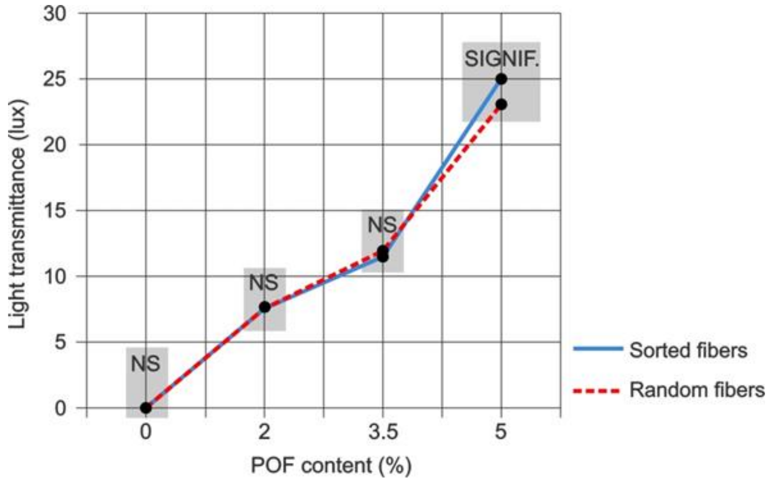

Figure 9. Average results of the light transmittance tests and the statistical analysis results via Duncan´ s method.

4. Results

In cementitious composites, the addition of polymeric optical fibers has, as main objective, to provide light transmittance requirements. According to the limits established in the experimental program, different POF levels (0%; 3%; 3.5% 5%) were tested in two types of fiber layout: sorted and random. In this way, some conclusions were made about the interactions of the variables applied in this comparative research.

- According to the tests and statistical analyzes carried out for the compressive strength characteristics, the influence of fiber arrangement (sorted and random) was not clearly significant in the samples. Only the 2% POF family showed a statistically significant difference between the two types of arrangements. Specimens with 3.5% POF showed to belong to the same family, regardless of the type of organization, as well as groups with 5% POF. There was, therefore, no clear evidence that the arrangement of the fibers changes the behavior of the composite for compressive strength efforts.
- In the analyzes made for tensile strength in flexion, for the sets that effectively adopted fibers (2%, 3.5% and 5%), only families with 2% POF showed a significant difference for their arrangement. Fibers within the 3.5% content were shown to be part of the same group regardless of the type of arrangement, as well as those belonging to the 5% POF content. There was, therefore, no clear evidence that the arrangement of the fibers changes the behavior of the composite for flexural tensile strength. With regard to the averages of the variation coefficients that presented slightly higher values, this phenomenon can be attributed to the intrinsic behavior of greater variability of conventional cementitious matrices to this type of efforts. The addition of POFs for both manners does not improve this property.
- The statistical results for the capillary water absorption, among the levels that effectively adopted fibers, again, only the 2% POF showed to have significant differences for the different arrangements. For the other contents (3.5% and 5% POF) there is no statistical difference

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between the fiber arrangements (random or sorted). So, it can be said that there is no clear evidence of statistical difference between groups with the same fiber content. This is particularly interesting, as this type of characterization is a parameter that indicates the durability of materials over time. Regarding the increasing means of the variation coefficients as more fibers are added to the composites, this fact may be linked to the transition zone in the fiber-matrix interface. This tends to present a level of porosity with greater variability for reasons not yet investigated. However, it is common knowledge that the pores (voids) in the cementitious matrix end up working as a water deposit, directly affecting the results of water absorption tests.

- For light transmittance, only the fibers arranged in random and sorted manners within the 5% POF content showed to belong to different families, with slightly higher values for the sorted ones. This is an interesting fact, because in specimens with random fibers, their accumulation in certain places may have influenced the light intensity measured by the luximeter, even though the number of POFs has remained the same in relation to the sorted samples. Thus, only for higher levels (5% POF), this difference was statistically perceptible.

In general, it can be concluded that for the analysis of mechanical behavior (flexural tensile and compressive strength) and durability (capillary water absorption), composites with sorted and random fibers within 2% POF content showed to belong to statistically distinct groups. As there was no pattern behavior for the other fiber contents adopted (3.5% and 5% POF), it cannot be said that there is a difference - up to the limitof 5% POF content - for both fiber arrangements in their mechanical and of durability performance. As for light transmittance, the statistical difference between fiber arrangements only in the 5% POF content can be attributed to their accumulation in certain points of the material, influencing their transmittance measured by the luximeter.

Therefore, the polymeric optical fiber, despite not being a material intended specifically for civil construction, can be adapted, both in an sorted and random manner, to make translucent mortar blocks without significant structural damage to the material's properties.

Author Contributions: Thiago Henriques: conceptualization, data curation, investigation, methodology, project administration, validation, visualization, writing-original draft, writing-review & editing; Denmise Dal Molin: conceptualization, formal analysis, investigation, methodology, project administration, supervision, validation, writing-review & editing; Angela Masuero: investigation, methodology, project administration, funding acquisition.

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Conflicts of Interest: The authors declare no conflict of interest.

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