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Mechanical Properties Study and Durability Indicators of Concrete with Polystyrene in Fine Aggregate Substitution

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Abstract-The aim of the developed article is evaluating the influence of using polystyrene as fine aggregate substitute in concrete production. To start the project it was adopted a concrete mixture ratio proportion as reference, and then determined polystyrene substitution rates in the concrete. Test specimens were made according to the reference ratio proportion and the analysis ones using 25 and 50% of polystyrene mass substituting fine aggregate. The substitution results were compared themselves and between parameters and reference values presented in technical manuals and scientific literature. It was possible to notice in the end of a 28 day curing process a 30% compression strength decrease of the test specimens with 25% of polystyrene substitution and 44% compression strength decrease of the specimens with 50% polystyrene substitution.

Keywords- *Concrete, Waste Reuse, Polystyrene*

I. INTRODUCTION

The ecologically material development and use of cleaner production ways concerning civil construction are an alternative to the grown necessity of fixing environmental problems [11]. Civil construction industry besides being a huge natural resources consumer, is one of the bigger wastes generator, which turns out the necessity of searching permanently for a system based on sustainability, focused on reducing its damages, even because of the environmental cause or restricted to the competition on the construction market [35]. Some of these actions are associated to productive process as obtaining basic raw materials, producing components and constructive elements related to the built space occupation and according to the user recommendations [34].

Considering recycling, its potential benefits in the civil construction universe are: consume reduction of non-renewable resources when exchanged by the recycled ones, less areas for residues deposits once the waste is reused as a consumer material, less energy demand during production process, pollution reduction, employment generation and earnings.

Polystyrene, which is also called expanded polystyrene (EPS) is a sort of plastic – polymer – derived from petroleum. This material is used in different economic areas, as industries, trade, civil construction and others. According with [36] polystyrene (PS) is included on thermoplastic resins which also includes polyethylene (high density; low density and low linear density), polypropylene (PP), polyvinyl chloride (PVC) and polyethylene terephthalate (PET).

The polystyrene is a polymer formed by the styrene polymerization in water, in this reaction is added an expansive element commonly called pentane. After the polymerization process done it results in polystyrene, also called expanded polystyrene, which is a stiff and tenacious material according to [31]. Is a plastic material in a foam form with micro-cells closed, basically compounded of 2% polystyrene and 98% empty spaces filled with air, its color is white, recyclable, non-pollutant, physically stable and works as a very good insulate material [36]. As this material has lots of empty spaces filled with air, EPS (expanded polystyrene) is one of the materials which presents huge volume and it's a problem related to storage and disposing it, because this traits require larger places in the landfill, besides taking too long to decompose itself [2].

Oliveira [27] says this material have gained a stable position related to building construction in the last 35 years, not only by its insulate traits but also its lightness, toughness, easiness to work and low cost. About the applications of expanded polystyrene in civil construction is noticed it offers advantages as thermic and acoustic insulate when adopted on walls and flagstones, it also brings lightness if used as aggregate in the concrete [21] and [22].

According with data from [28], it was produced in Brazil 82,9 thousand tons of polystyrene. From this value is estimated that seven thousand tons, which is 8,4% of the total, returns to the process by recycling.

According to [12], [14] and [30], the aggregate can be defined as the revetment systems skeleton executed, it intervenes directly on mechanical strength, deflection modulus and other properties. As [24], [30] and [32] they affirm the aggregate provides an internal resistance in the mixture, with capacity to resist to internal tension borned by the volume changing, when the mortar is in drying process, being responsible by the cracking strength from the hydraulic shrinkage.

The aggregate substitution influences the good performance of cement's compounds and it depends, mainly, of a good grain distribution [29], the aggregate's form [19] and [24] and the package processing method [18], [26] and [33] permits minimizing the mixture porosity and guarantees the minimum binder paste utilization to compacity improvement.

There were made some experiments by [16] adding water in the optimum rate of the dry materials in order to evaluate if it would be the best rate, he concluded that: in adding water to the dry mixture the reaction properties may be considered; the dry granular mixture package density, which influence plastic viscosity; the runoff tension is more influenced by the fine particles than by the package density and the quantity of fine sand is reduced in paste presence.

For [33], the granulometric distribution influences the package density, the cement compounds' physical properties and refractory systems. As [15] says, the discontinued granulometry doesn't produce better package nor a little void index, but it gives fluidity with less water content in the mixture as function of a bigger mobility and less intern friction between the aggregate particles.

The present study's goal is to make a quantitative determination of concrete with EPS (expanded polystyrene) performance as recycled fine aggregate. To achieve this goal there will be made some tests using a test specimen with a fixed rate, without EPS addiction, as reference, this will be compared with the others test specimens, technical manuals and scientific literature.

II. MATERIALS AND METHODS

Considering the proposed objectives it was adopted an experimental and comparative method. There were made aggregate characterization tests, dosage and analysis of fresh and indurated concrete using EPS residue substituting (0, 25, 50%) of the natural fine aggregate.

A. Materials

The materials used to make the reference concrete (Recipe I) and the substituted ones were: Cement CPII E 32 from Holcim; coarse aggregate gravel zero, gneiss from a quarry in the city of Esmeralda, Minas Gerais; natural quartz sand from Paraopeba's riverbed also from Esmeralda's city, Minas Gerais, ABNT NBR 7211: 2009, Table 1. The artificial fine aggregate used was the one from the milled expanded polystyrene obtained by its clean material wastes. Visually its granulometry has the natural's fine aggregate dimensions and the density adopted for it was 25 Kg/m³, according with [1].

Table 1 presents the concrete recipe used as reference (Recipe I), the same recipe was used as reference for all the concretes with EPS, but part of the fine aggregate was substituted in volume. The experiments for the recipe with no EPS substitution, 0% EPS (Recipe I), 25% EPS substitution (Recipe II) and 50% EPS substitution (Recipe III) were compared in a way the obtained results could provide conclusions about its characteristics considering strenght, porosity, workability, density and concrete's absorption.

TABLE I. USED AGGREGATE CHARACTERIZATION

Granulometric Composition (NBR NM 248:2003)		
Sieve - orifice (mm)	Fine Aggregate	Coarse Aggregate
Classification	Optimum Region	Gravel Zero
Maximum diameter	4,8	12,5
Fineness modulus	2,32	5,8
Real specific mass (NM 52:2009)	2,59 kg/dm³	2,68 kg/dm³
Unit specific mass (NM 45:2006)	1,34 kg/dm³	1,46 kg/dm³
Clay content (NBR 7218:2010)	0,65%	0,00%
Powder material content (NM 46:2001)	2,86%	0,70%
Organic impurity (NBR NM 49:2001)	< 300 p.p.m.	<300 p.p.m.

All the test specimens used in this experimental program were made in the UFMG Concrete Laboratory, they remained in the wet room until 24 hours before the tests.

The aggregate characterization correspond to the granulometry, specific mass, powder material, absorption, stereoscopy magnifying glass images. It was also described the mineralogical composition using X-ray diffraction and X-ray efflorescence.

Natural aggregate is found in an optimum region, its maximum diameter is 4,8 mm. In the X-ray diffraction and the X-ray efflorescence was possible to see abundant quartz (SiO_2; trigonal), a middle-low percentage orthoclase ($Na_{0.8}Ca_{0.2}Al_{1.2}Si_{2.8}O_8$; triclinic), low albite index ($NaAlSi_3O_8$; triclinic), low caulinite index ($Al_2Si_2O_5(OH)_4$; monoclinic), little iron-homblenda concentration ($Ca_2Fe_2+4Al_{0.75}Fe_3+0.25(Si_7AlO_{22})(OH)_2$; monoclinic) and low goethite trace (FeO(OH), orthorhombic).

The coarse aggregate is gravel zero, with maximum diameter of 12,5 mm and the following mineral composition: abundant oligoclase (feldspar: $Na_{0.8}Ca_{0.2}Al_{1.2}Si_{2.8}O_8$; triclinic), quartz in a middle percentage (SiO_2; trigonal), moddle-low iron-homblenda percentage (amphibole: $Ca_2Fe_2+4Al_{0.75}Fe_3+0.25(Si_7AlO_{22})$ $(OH)_2$; monoclinic), biotite in a middle-low percentage (mica: $K(Mg,Fe_2+)3AlSi_3O_{10}(OH)1.75F_{0.25}$; monoclinic), low chamosita contents (chlorites: $Fe_2+3Mg_{1.5}AlFe_3+0.5$ $Si_3AlO_{10}(OH)_8$; monoclinic).

There were made three recipes with different concretes, one of them using natural fine aggregate and two others with artificial EPS aggregate substituting 25% and 50% of the fine aggregate volume. The mass rate recipe was: 1,000:1,830:2,850:0,550. Three ages of the curing process were analyzed 7, 14 and 28 days as shown on Table 2.

TABLE II. EXPERIMENTS SUMMARY

Tests	Age (days)
Axial compressive strength (NBR5739: 2007) Traction by diametric compression strength (NBR7222: 2011) Dynamic elasticity modulus (NBR 8802:2013) Ultrasonic waves propagation velocity (NM 58/1996)	7 / 14 / 28
Capillary suction absorption (NBR 9779: 2012) Immersion absorption (NBR 9778: 2012)	28

The concretes characterization corresponded to the axial compressive strength, traction by diametric compression strength, porosity, elasticity modulus by ultrasound, immersion absorption, capillarity absorption and stereoscopy magnifying glass images.

III. RESULTS AND ANALYSYS

A. *Specific mass*

Specific mass was evaluated for all test specimens with 28 day curing process age, each different recipe presented a different value for this parameter. Recipe I, the reference one, has 2500±0,015 Kg/m³, Recipe II 2300±0,017 kg/m³ and Recipe III 2200±0,015 Kg/m³. Specific mass in Recipe II was around 9% smaller then Recipe I and the Recipe III one was 14% smaller than the Recipe I.

Expanded polystyrene when compared with natural sand has little density, so less specific mass in Recipes II and III comes from the partial substitution of the fine aggregate by the EPS. Nevertheless specific mass reductions wasn't so expressive, it may have happened because the water amount stored in the Recipes II and III of the test specimens was bigger than in Recipe I. Once there was less water incorporation in EPS grains in comparison to sand, it happens in order to the EPS non-polar traits.

Relative to the EPS deformation capacity comparing it with the other mixture components it caused a bigger shrinking of the polystyrene particles and the non-incorporated water evaporation which caused the little specific mass reduction on the substituted concretes. This reduction wasn't relevant enough to change the characterization from normal concrete to light concrete, according to Mehta and Monteiro (2008).

B. *Workability*

The three Recipes were made with the same water volume, this factor influences directly the concrete workability, it was possible to measure that Recipe III presented bigger slump than Recipe II and this one by itself presented bigger slump than Recipe I, as can be seen in Table 3.

The slump occurred without materials disaggregation, which confirms the recipe adequate composition. The expanded polystyrene besides its high porosity has a low water absorption in order its non-polar traits. This low water absorption promoted the workability rising in Recipes II and III when compared with the reference one, Recipe I.

According to the technical manual ABNT NBR 8953: 2011, which classifies concretes' workability by the slump measure in the slump test, Recipes I and II presented very low workability degree as long as Recipe III showed middle one.

TABLE III. RESULT DO SLUMP TEST

Recipe	*Slump* (mm)
I (reference)	0
II (25% substitution)	30
III (50% substitution)	100

C. *Axial Compressive strength*

Concerning the axial compressive strength, in a general way, the age development promoted strength increasing. Figure 1 presents the representative regressions and adjusts for the behavior analyzed by the test.

For Recipes I and II the best adjust was obtained by a logarithmic curve, the Recipe III has the best adjust by an exponential function. Is possible to see that Recipes I and II presented around 70% of the final strength after seven curing days and 85% of it after 14 days. This feature can change the demanded time for the concrete to be charged, it could expedite the curing process. Figure 2 shows correlation between fc and the substitution percentage.

The Figures 1 and 2 show clearly the compression strength decreasing as the fine aggregate is substituted by expanded polystyrene. The range between Recipes I and II strength is almost constant during the days. Recipe II presents 30% less strength than the reference recipe. Between the reference and Recipe III there is a fluctuation in the strength difference, as Recipe III has the smaller strength increasing rate. After 28 days Recipe III presented the smaller strength between the tests specimens, it was around 44% smaller than Recipe I and 25% smaller than Recipe II.

According to [23], Van der Waals attraction strength is responsible for the chemical adhesive strength between the moisturizing products and the aggregate particles. There is also the mechanical attachment created by the cement moisturizing, specifically from the etringite which interlock the aggregate pores.

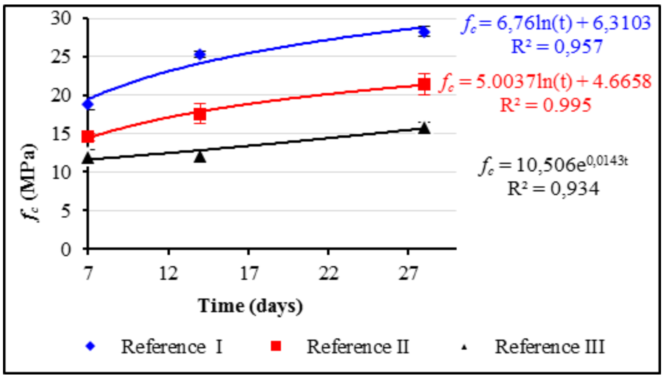


Figure 1. Axial compressive strength evolution with the specimen age

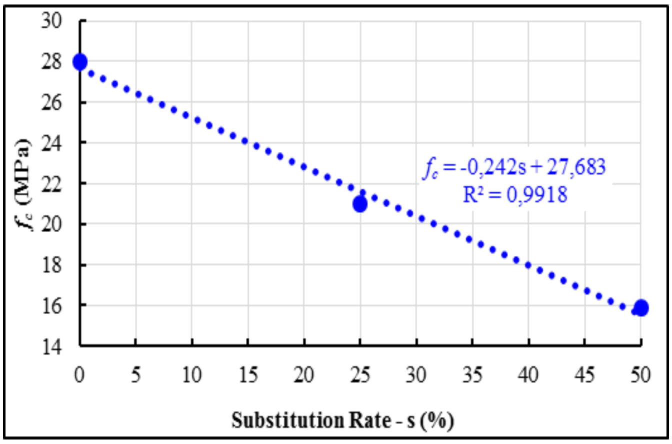
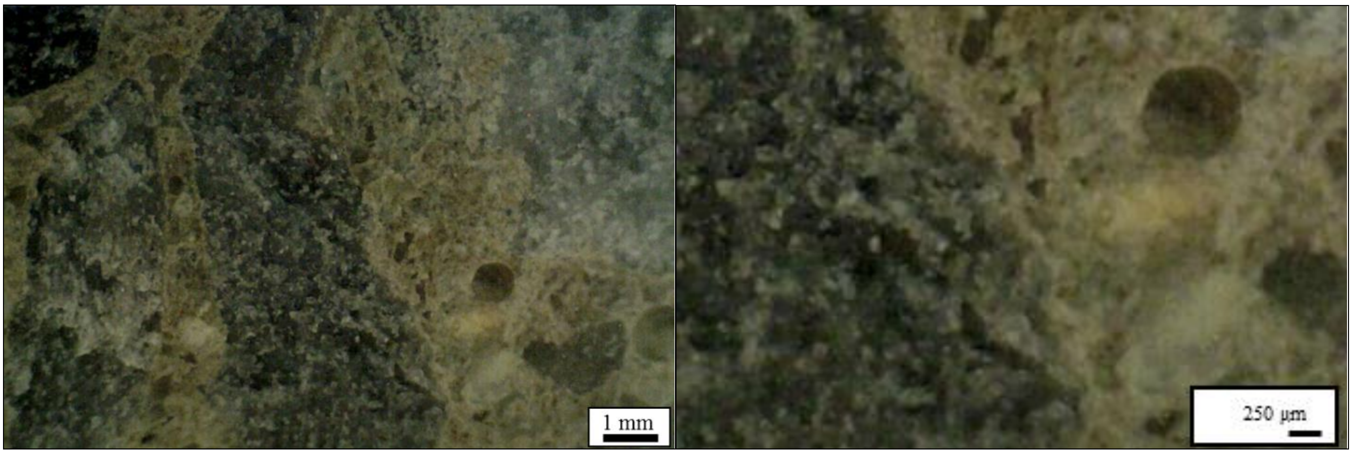


Figure 2. Correlation between axial compression strength and aggregate substitution rate

Therefore strength in any transition zone depends on shape and size of the aggregate's voids. The stereoscopy magnifying glass images taken by the three recipes are presented on Figure 3 (a) e (b), 4 (a) e (b) e 5 (a) e (b).

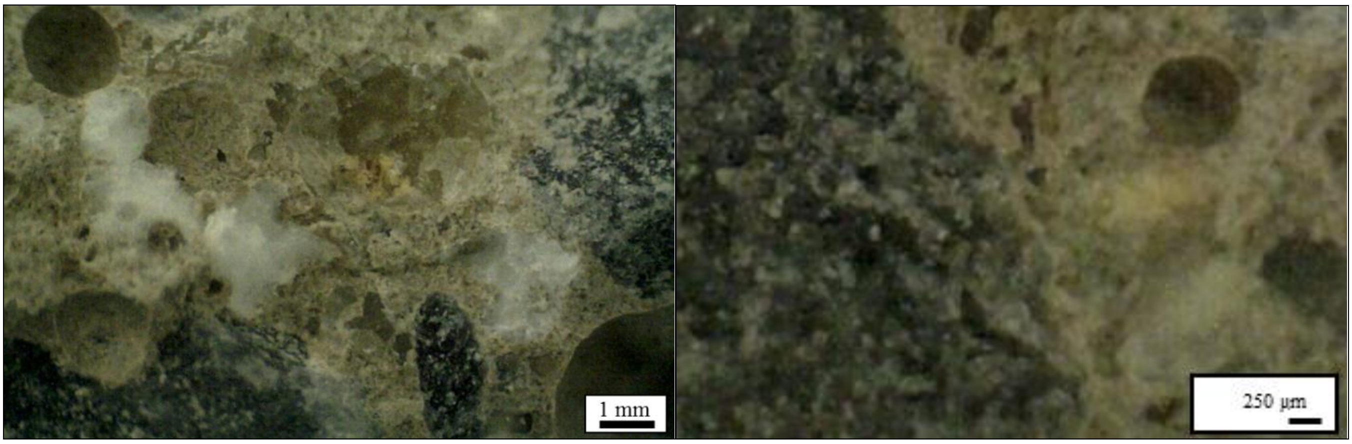
By the images is possible to see a bigger voids number in Recipes II and III when compared with Recipe I, even more in the transition zone band. Is also important observe the pore sizes range. In Recipe I there were identified pores around 250µm, in Recipe II there are pores bigger than 3mm.

In Recipe III, one more time, is possible to visualize pore reduction, but here is a high voids occurrence on the artificial aggregate surface which happens in order to the aggregate's non-polar traits relative to the water. Less strength, voids related to water presence and aggregates' non-polarity are reasons why the lower strength happened in the recipes with EPS substitution.



(a) (b)

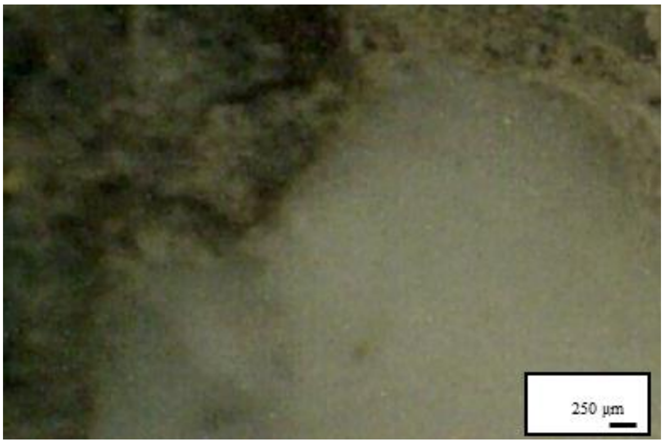
Figure 3. Recipe I (reference) Microstructure



(a) (b)

Figure 4. Recipe II (25%) Microstructure.

(a)



(b)

Figure 5. Recipe III (50%) Microstructure

D. Traction by diametric compression strength

Traction by diametric compression strength reveled correspondent characteristics as the ones observed for axial compression, even about the adjusts used for each one of the recipes or about the relative behavior of them. Figure 6 presents the ft values associated of each recipe variance of the analyzed ages.

The strength loss on Recipes I and II is stable around 20% and after 7 curing days they present almost 85% off its final strength. Recipe III has 80% off its final strength after the 7 days. In addition to this is important to say, in the end of the 28 curing days Recipe III has similar strength to Recipe II and 22% smaller than Recipe I, Figure 7.

On the specimen's breaking tests the reference recipe presented concentrated and unidirectional crack propagation. In the specimens with expanded polystyrene substitution there was a bigger crack amount around the EPS particles, it happened even in diametric or axial compression, which have detected a weakness in the mixture.

According to [17], [23] and [25] the linkage between traction and compression strength turns around 10 to 11% for low strength concrete and 8 to 9% for middle strength concrete.

Figure 8 shows the connection found between compression and traction for the three recipes. Is possible to see Recipes I and II doesn't follow the mentioned connection, Recipe III presented a 4% correlation and Recipe I a 2% one.

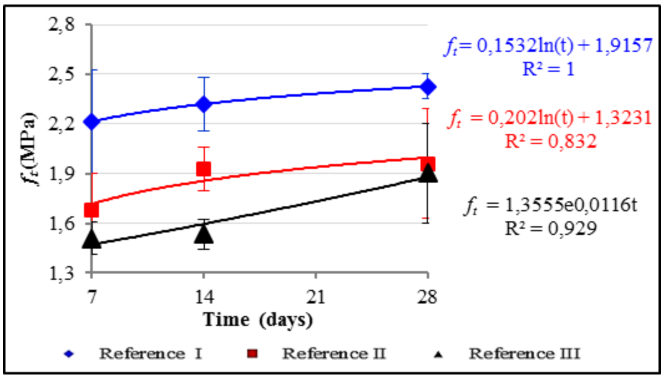


Figure 6. Traction by diametric compression strength Evolution

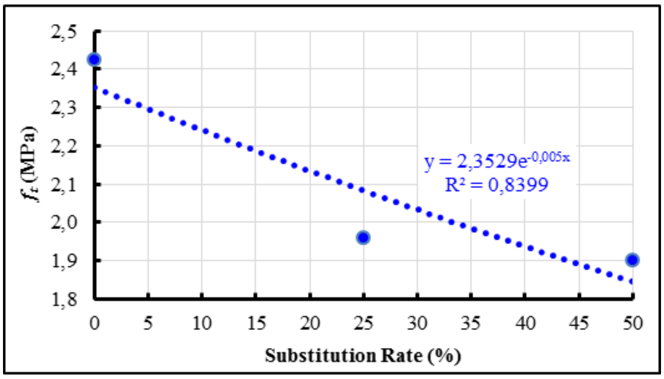


Figure 7. Correlation between traction by diametric compression strength and fine aggregate substitution rate

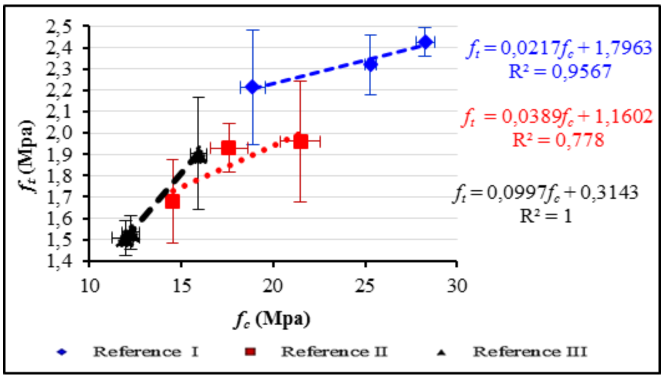


Figure 8. Linkage between axial compression and diametric strength

Only Recipe III presented a percent ratio according to the 10% referrals. It was identified on the experiments this specimen presented little more fluidity and cohesion than Recipes I and II, which could be the reason for the traction strength increasing.

E. Water absorption by immersion

Water absorption by immersion test evaluates the water absorption during a specific time and its porosity comparing the dry and saturated mass of the specimen. This test was done according to [7], using a 96 hour permanence immersion time. Figure 9 presents the tests results with the three recipes. Recipes II and III presented a higher absorption in comparison to Recipe I, which shows a water absorbed increasing of 87% in Recipe II and 148% in Recipe III comparing with the reference one, Recipe I.

Is known the aggregate substitution in a cement paste rises the mixture permeability, even bigger is the aggregate's size, bigger is the permeability coefficient. The polystyrene's granulometric distribution is more uniform than the sand's, which could be the reason for the concrete permeability rising.

F. Porosity

Figure 10 shows the porosity tests results, a significant error in the recipes could have happened during the concrete's homogenization and densification process in order to the use of an extremely light materials as EPS.

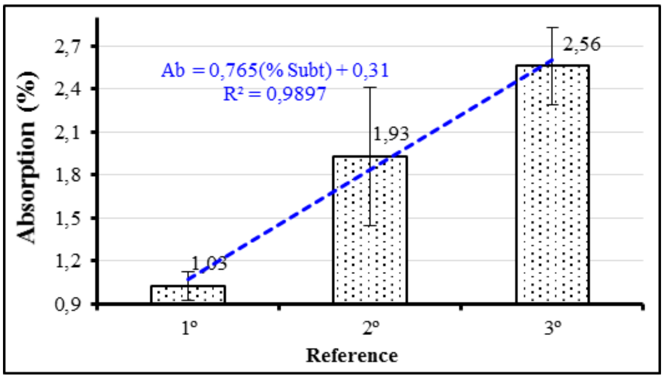


Figure 9. Water immersion absorption

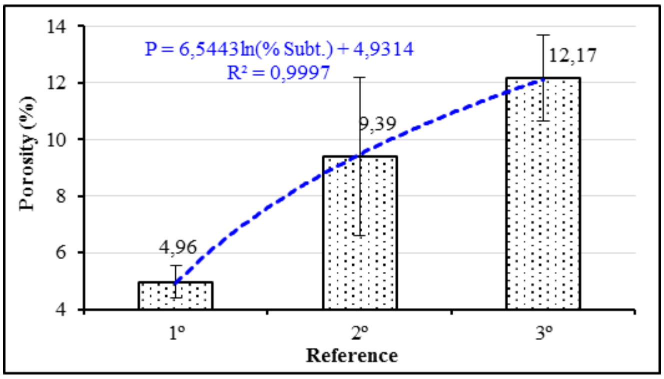


Figure 10. Concrete's superficial Porosity

Partial substituted concrete's porosity is bigger than the reference concrete's. Recipes II and III has shown bigger porosity than Recipe I (reference specimen), it's percent rising was of 89% and 145 %, respectively.

In Recipes II and III there is a less specific mass of substituted aggregate, which has a huge voids volume (98%). This substituted concrete voids rises the composite porosity, in addiction to it there is a bigger water remain in the mixture (slump rising), it could have produced pores in the structure to promote the water evaporation, water loss. Is known the Recipes' II and III porosity has a direct influence on its concretes strength in comparison to Recipe I, by the analyzed microscopic images can be noticed the difference between the voids amount in each of the three recipes.

G. Capillarity water absorption

The capillarity water absorption test for the investigated mixtures after 10 minutes, 90 minutes, 3h, 6h, 24h, 48h and 72h of the 28 day curing process are shown in Figure 11.

Analyzing Figure 11, it is possible to verify in a general way the capillarity absorption in Recipes II and II presents bigger values (rising of 260% e 330%, respectively) than the reference recipe. In the microscopically images from Figures 3, 4 and 5 it is possible to see EPS changed the pore structure (several interlinked pores), this change caused the concrete's capillarity absorption (permeability) rising. Besides what was proved by the sharp absorption stabilization on Recipe I when compared to the substituted recipes, which continue promoting pores' capillarity percolation.

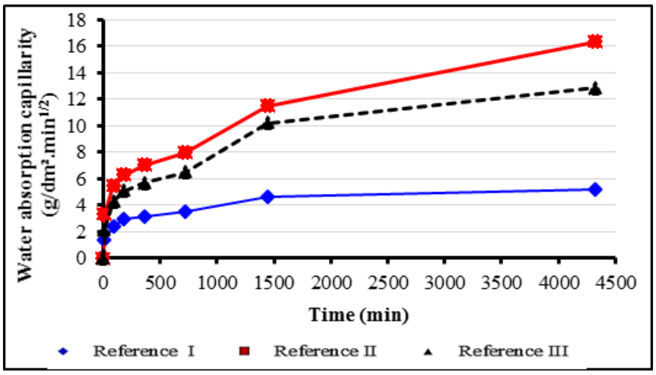


Figure 11. Water absorption capillarity (g/dm².min$^{1/2}$)

The following Figure 12 presents the capillarity coefficients' values obtained for the three different recipes. Once again the large variation comes from the hard recycled aggregate homogenization in the tests specimens. It generated inconclusive data concerning this parameter, which turned the data fluctuation little significant.

H. Wave ultrasonic propagation speed

Using the wave ultrasonic propagation speed results (Figure 13), is possible to see that concretes without fine aggregate substitution (Recipe I) presented the biggest wave propagation speed when compared with the other ones. Confirming this affirmative Recipe III correspondent concrete has shown smaller wave propagation speed which demonstrate the EPS presence turned up the wave propagation time minimizing its speed in order to the expanded polystyrene low specific mass, which create less dense compounds.

Elasticity modulus and compression strength's concrete are straightly linked because cementations matrix porosity rising and the EPS addiction causes significant reduction of the referred parameters. The most important factors that are related to both parameters are intrinsic to the evaluated material, it can be mentioned the aggregate and cement type and quantity used, humidity ratio, concrete temperature and the material surface conditions.

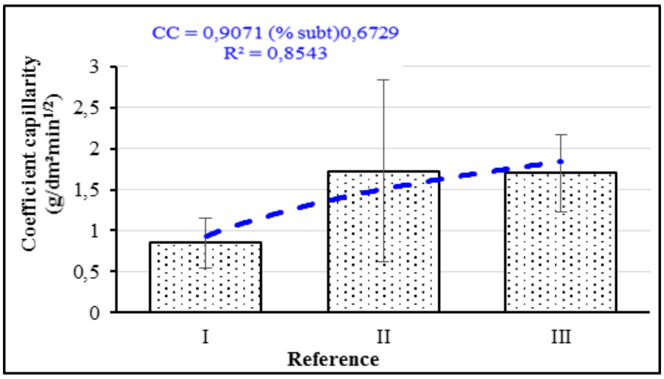


Figure 12. Capillarity Absorption

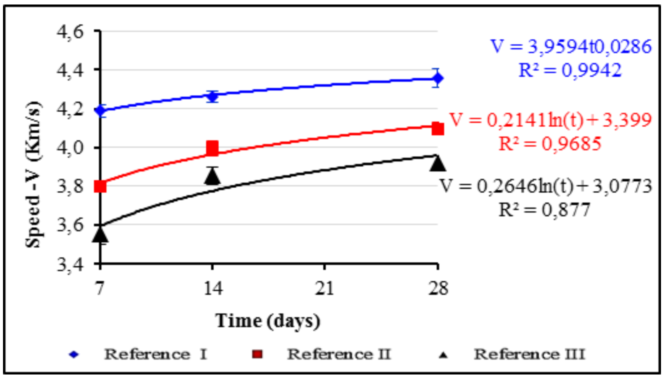


Figure 13. Wave ultrasonic propagation speed

Figure 14 presents the dynamic elasticity modulus for each different recipe. Is important to say this data correspond to the obtained results for wave ultrasonic propagation speed values. In this case, the recycled aggregate rate in each recipe changed mainly the dynamic elasticity modulus.

Figure 15 combines elasticity modulus values found by ultrasonic pulse with axial compression values. The elasticity modulus in the recipe with expanded polystyrene has a little bit stronger grown than the elasticity modulus from the reference recipe. This phenomenon happens because of the less mass relation between binder and aggregate in the substituted recipe which demand higher cement consumption for moisturizing.

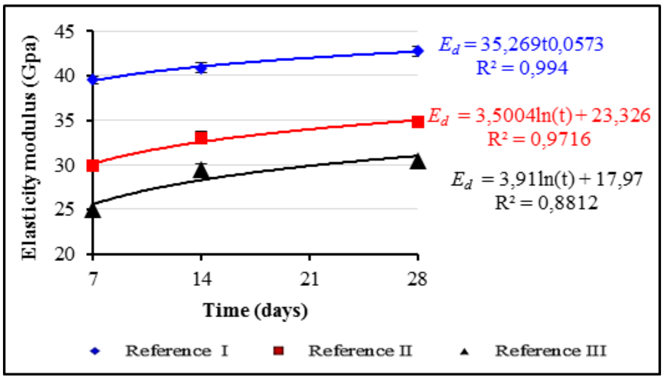


Figure 14. Dynamic elasticity modulus

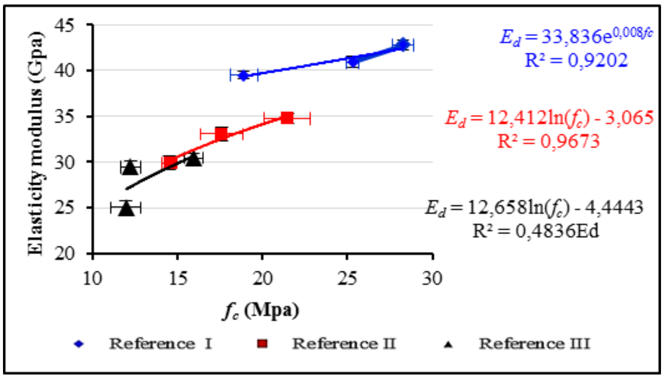


Figure 15. Linkage between elasticity modulus and compression strength

The elasticity modulus grown between 7 and 14 days was of 8% in Recipe I, 16% in Recipe II and 22% in Recipe III. It is possible to verify that the elasticity modulus values has grown slowly that the strength ones. As [25] the aggregate's elasticity modulus changes the shrinkage magnitude and the composite fluency. A polystyrene's and sand's modulus are different because of each material specific characteristics, it could have emphasized micocracks development on the aggregate interface substituted concrete matrix, reducing its strength and elasticity modulus.

IV. Conclusions

The obtained results of this study have shown an expressive decrease of the mechanical properties and durability related to the partial substitution of the natural fine aggregate for the expanded polystyrene. The traits for the specimen with 25% of EPS incorporated presented more uniform behavior during the tests, less variability than Recipe III and the best results on the tests with strength emphasis. Besides the resistance decrease, the partial substitution of fine aggregate for EPS improved the concrete workability.

The porosity increasing in concretes with EPS is evident, and the rifts conditions, discontinuance and clefts have had its expansion maximized, because EPS doesn't have high rigidity. As porosity increasing consequence relative to the partial substitution of natural fine aggregate for expanded polystyrene there was an increasing of water mass in the absorption by immersion test by the specimens substituted when compared with Recipe I.

Is important to say the resistance decreasing presented doesn't permit the concrete with EPS to be used with structural purpose, but even though it presents applicability in situations that demand less strength as floor fillings and flagstones. Therefore there is a technical variability related to the partial substitution of fine aggregate for the EPS.

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