UNIVERSIDADE FEDERAL DO RIO GRANDE DO NORTE

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LOW CEMENT STRUCTURAL LIGHTWEIGHT CONCRETE WITH OPTIMIZED MULTIPLE WASTE MIX DESIGN

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PhD Thesis submitted to the Universidade Federal do Rio Grande do Norte as a partial requirement to obtain the PhD degree

Advisor: Prof. Antonio Eduardo Martinelli

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ABSTRACT

The high-energy demand involved in the construction industry and the increasing consumption of concrete made this material an ideal option for the recycling of by-products from various industries such as: porcelain polishing residue (PPR); tire rubber residue (TRR) and limestone residue (LSR). These residues often lack a treatment that contributes to the degradation of the environment. In this sense, the use of by-products that increases the volume of the concrete without damaging significantly its properties, can be a viable option in the production of low-cost and sustainable low-weight concrete (LWC). The main objective of this work was to analyze the mechanical and thermal behavior of structural lightweight concrete (SLWC) with low cement consumption, produced with expanded clay (EC) in replacement of the aggregate and with the addition of PPR, TRR and LSR to replace the small aggregate. For this purpose, a 2^3 factorial design was used for the choice of SLWC with the best performance in terms of consistency, mechanical properties and density. Subsequently, reductions of 10, 20 and 30% of cement were performed on SLWC that presented better combination of properties and waste consumption and were characterized by mechanical tests. The best SLWC mix resulting from the combination of mechanical properties and cement consumption was characterized by permeability, flexural strength, TG/DTA, XRF, SEM, thermal capacity, thermal conductivity and thermal diffusivity. The results showed that residues contents around 21% presented better combination of properties. By maintaining the amount of residue at optimum levels it was possible to produce a SLWC with good rheological, mechanical and thermal properties with minimum cement consumption.

Key-words: Structural lightweight concrete; porcelain tile polishing residue; tire rubber residue. Limestone residue

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RESUMO

A alta demanda energética envolvida na indústria da construção civil e o crescente consumo do concreto, fez com que o concreto se tornasse a opção ideal para a reciclagem de subprodutos de várias industrias tais como: resíduo de polimento de porcelanato PPR; resíduo de borracha de pneu (TRR) e resíduo de pedra calcária (LSR). Esses resíduos frequentemente carecem de um tratamento adequando o que acaba contribuindo para a degradação do meio ambiente. Nesse sentido, o uso de subprodutos que irão aumentar o volume do concreto sem prejudicar muito as propriedades, pode ser uma opção bastante viável na produção de Concretos leves (CL) de baixo custo e sustentáveis. O objetivo geral desse trabalho foi analisar o comportamento mecânico e térmico de concretos leves estruturais (CLE) de baixo teor de cimento produzidos com argila expandida (AE) em substituição ao agregado graúdo e com adição de PPR, TRR e LSR em substituição a parte do agregado miúdo. Para tal foi usado inicialmente um planejamento fatorial 2^3 para a escolha dos CLE com melhor desempenho em termos de consistência, propriedades mecânicas e massa específica real. Posteriormente foram realizadas reduções de 10, 20 e 30% de cimento nos CLE que apresentaram melhores desempenhos e caracterizados através de ensaios mecânicos. O melhor traço resultante da combinação de propriedades mecânicas com o consumo de cimento foi caracterizado mediante ensaios de: permeabilidade; resistência à flexão; TG/DTA; FRX; MEV; capacidade térmica; condutividade térmica e difusividade térmica. Por fim. Os resultados mostraram que teores de resíduos em torno de 21% apresentaram melhor combinação de propriedades. Mantendo os teores de resíduos em níveis ótimos foi possível produzir um CLE com boas propriedades reológicas, mecânicas e térmicas com um consumo mínimo de cimento.

Palavras-chave: Concreto leve; Concreto leve estrutural; Resíduo de polimento de porcelanato; Resíduo de pedra calcária; Resíduo de borracha de pneu.

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LIST OF ABBREVIATIONS AND ACRONYMS

AE	Argila expandida
ANFACER	Associacao Nacional de Fabricantes de Ceramica
BFS	Blast furnace slag
CL	Concreto leve
CLE	Concreto Leve estrutural
CC	Cellular concrete
CP	Concreto Padrão
DTA	Análise Térmica Diferencial
EC	Expanded clays
EPS	Expanded polystyrene
FA	Fly ash
FLWA	Foamed lightweight aggregates
FRX	Fluorenscência de Raios X
HPLWC	High performance lightweight concrete
HSLWC	High strength lightweight concrete
LCR	Lightweight concrete with residue
LSR	Limestone residue
LWA	Lightweight aggregates
LWAC	Lightweight aggregates concrete
LWC	Lightweight concrete
MEV	Microscopia Eletrônica de Varredura

MC	Metacaulin
NSLWC	Nonstructural lightweight concrete
OC	Ordinary concrete
PF	Polypropylene fibers
PPR	Porcelain tile polishing residue
PS	Pome stone
RC	Reference concrete
SCC	Self-consolidating concrete
SCLWC	Lightweight self-compacting concrete
SF	Silica fume
SLWAC	Structural lightweight aggregate concrete
SLWC	Structural lightweight concrete
TG	Análise Termogravimétrica
TRR	Tire rubber residue
TF	Trace final

SUMMARY

1 INTRODUCTION

In recent years, concrete formulation has been one of the main ways of recycling various wastes that were previously discarded in the environment (SAMPAIO, 2014). The high energy demand involved in the construction industry (LIU et al., 2014) and the increasing consumption of concrete made this material the ideal option to recycle by-products of various industries such as: porcelain tile polishing residue (PPR); tire rubber residue (TRR) and limestone residue (LSR).

Porcelain tile is a ceramic coating that, due to its physical and chemical characteristics, has been used as an alternative product to granite and other natural stones. In the process of manufacturing porcelain tiles, more specifically in the polishing of the pieces, the PPR is generated (KOCKAL; OZTURAN, 2011a). The PPR contains toxic metals from the manufacturing process being classified as class I and class IIA by NBR 10004 (ABNT, 2004), thus needing managed disposition. The high cost involved in the proper disposal of this waste has often led to its discard in the environment. This practice has been causing great social and environmental concern since Brazil is the second largest consumer and world producer of porcelain tiles (ANFACER, 2015). Studies have shown great potential of PPR application due to its pozzolanic activity (reaction with the $Ca(OH)_2$ of the cement) (ANDREOLA, 2010)(SILVA, 2012).

Studies have also been carried out with mining and processing of rocks waste such as limestone residue (LSR), which are generally discarded in lakes, rivers, highway domains and around mining companies. Limestone is a rock composed basically of calcite, whose chemical composition is calcium carbonate (SILVA, 2009). Limestone is used in construction as a raw material in the manufacturing of lime, cement, ceramics and in agriculture as a corrective of acid soils. In the last years (2003-2008) there was a growth of 22% in limestone production in Brazil, reaching a total of 107 million tons in 2008. The forecasts indicate that this trend may be maintained (SILVA, 2009). The waste generated by the limestone treatment in the miners are in the order of 11% by mass of the total produced (DNPM, 2006). Forecasts indicate that waste production is expected to increase from 14 million in 2015 to 20 million by 2030 (SILVA, 2009). However, to date, there is a considerable lack of studies about this material.

Tire rubber residue (TRR) is another material that has undergone a considerable increase due to the worldwide increase of the fleet vehicles. According to DENATRAN (DENATRAN, 2015). Brazil has a fleet of 87.3 million vehicles and in the last ten (10) years the country recorded a growth of 119%. Normally TRR is discarded in landfills, however, due to the difficult decomposition of this material and the considerable reduction in the life of the landfills with this practice, this type of disposal has been shown to be ecologically unviable (YUNG; YUNG; HUA, 2013). Several alternatives are already being used in the construction industry to manage the TRR, including asphalts and sports floors, road barriers, sound insulation panels and expansion joints (MARQUES; CORREIA; DE BRITO, 2013).

Although the use of TRR is not feasible as a structural material since it considerably reduces the compressive strength (MARQUES; CORREIA; DE BRITO, 2013)(WANG; CHEN; WU, 2013)(ISSA; SALEM, 2013)(ALBUQUERQUE, A. C.; ANDRADE, W. P.; HASPARYK, N. P.; ANDRADE, M.A.S.; BITENCOURT, 2006), Researchers have demonstrated great potential of its use in other areas, especially vibration damping, impact resistance, fire resistance, thermal insulation in façades, among others (SIDDIQUE T. R., 2004)(MARQUES; CORREIA; DE BRITO, 2013)(WANG; CHEN; WU, 2013)(ISSA; SALEM, 2013). However, these efforts are not sufficient to account for the amount of TRR produced each year, which reinforces the need for further studies to increase its application.

Aggregates occupy 70 to 75% of the weight of the concrete resulting in an annual consumption of 7.5 billion tons. Therefore, the use of waste from other sectors as part of this material could represent a significant improvement in the sustainability of the construction industry. Barbudo et al.(2013) reported in their studies that the mechanical properties of the concretes were not significantly altered with the substitution of up to 25% of the aggregates.

Currently, 8 million ton of concrete and 2.8 billion tons of Portland cement are produced per year (PELISSER; STEINER; BERNARDIN, 2012), which results in an average consumption of 0.8 tons of clinker per ton of Portland cement produced (MEHTA, P. K,; MONTEIRO, 2008)(PELISSER et al., 2012). Annually, the CO_2 emissions associated with cement production can reach almost 2.2 billion tons, which is almost 6% of total CO_2 global emissions (ROADMAP, 2009).

According to the 13th International Conference on Chemistry of Cement (2011), in 2025 the cement industry will emit CO_2 at a rate of 3.5 billion tons/year (MARLAND, G.; BODEN, T. A.; ANDRES, 2008), and in 2050, the estimation of CO_2 emissions from the cement industry will be 17% of the global emissions (SURVEY, 2010). Currently concrete and mortars are practically considered as “green” materials due to the use of residue from other industries, capture CO_2 from the atmosphere among other benefits.

Lightweight concrete (LWC) has gained wide acceptance in the construction market due to its innumerable advantages over conventional concrete, which include: reduced concrete weight, increased working area (due to the reduction of the dimensions of the structural parts), handling and less costly transport operations, increased thermal and acoustic insulation and fire resistance (BOGAS; DE BRITO; FIGUEIREDO, 2015).

In the production of lightweight concretes, all aggregates are usually replaced by lightweight aggregates (LWA), which considerably reduces the density of the material (SHAFIGH et al., 2014). Concretes with density below 2000 kg/m^3 are usually considered LWC (NEWMAN, 2005). On the other hand, ACI 213R-03 (ACI 213R-03, 2003) defines the density range between 1400 and 1850 kg/m^3. The replacement of normal aggregates by low density aggregates in the production of LWC decreases the compressive strength due to the low strength of these aggregates (MEHTA, P. K,; MONTEIRO, 2008). Reducing concrete density while maintaining the material strength at acceptable levels, without increasing cement consumption (which raises the cost of concrete production), is a real practical challenge. In this sense, the use of by-products that increases the volume of the concrete without drastically impairing properties such as strength and weight can be a viable option in the production of low-cost and sustainable lightweight concrete.

The main objective of this work was to analyze the mechanical and thermal behavior of lightweight concretes with low cement consumption, produced with expanded clays (EC) replacing the coarse aggregate and PPR, TRR and LSR, replacing the fine aggregate.

2 LITERATURE REVIEW

2.1 LIGHTWEIGTH AGGREGATE (LWA) AND LIGHTWEIGTH CONCRETE (LWC)

Lightweight aggregate represent today a significant part of the total quantity of the aggregates used in construction industry. The low density (generally lower than 1800kg/m³) of this material provides several advantage, improved thermal insulating properties, acoustic insulation, reduced own weigh, among others (DUCMAN; MIRTIC, 2009). According to Ducman and Mirtic (2009), depending on its density the LWA can be used in the:

- Production of lightweight concrete, precast concrete products among others;
- Rehabilitation of buildings of historical importance;
- Increase the earthquake resistance of the buildings
- Several applications, where material with a low self-weight is specified by the designer

In the production of most LWA it is necessary to use additives, which can either cause the foaming or bloating of the material or thermal treatments to increase porosity. The increase in porosity causes a substantial decrease in the density of this materials resulting in LWA. Among the various materials that can be used as LWA it can be highlighted: EC, TRR, pome stone (PS), expanded vermiculite (EV), expanded polystyrene (EPS).

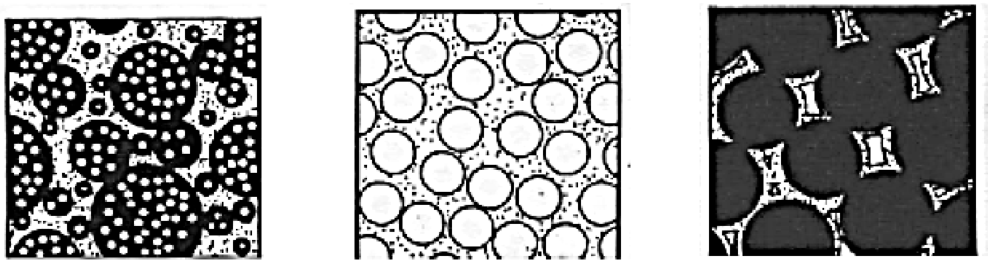
In recent years, with the emergence of environmental awareness, more efforts have been directed at studies and use of LWA from residues sources. Ducman et Mirtic (2009) explain that there are two reasons for this: (i) to reduce production costs by replacing natural raw materials with waste materials, and (ii) to re-use waste materials instead of putting them into landfill and paying additional environmental taxes.

LWA are classified into two types: natural (pumice, diatomite, volcanic ash and others) and artificial (perlite, clay, sintered fly ash, expanded shale and others). However, LWA from artificial origin are more used because they are easier to find although they are more expensive. In the civil construction industry LWA are used mainly in the manufacturing of LWC, mortars and filling.

The LWC has been widely used in many construction applications such as panels, walls, roofs, decks and precast. The reason for this versatility is due to its low density, low thermal conductivity, proper weight reduction, fast construction and low transport cost (JITCHAIYAPHUM et al., 2013)(ISLAM et al., 2016; KHANKHAJE et al., 2016; KOCKAL; OZTURAN, 2011b; SHANNAG, 2011). LWC are produced replacing common aggregates with LWA, incorporating air or foaming products. In all cases, it is necessary to increase voids inside the concrete so that the density can decrease.

To be considered as LWC, the material must have density less than 2000 kg/m³ (RILEM, 1975, CEB-FIP, 1977 and NS 3473, 1992). Some authors are more specific, adding that it should not have low density as well as compressive strength ranging from 1 MPa to cross sections as 60 MPa and thermal conductivity from 0.2 W/mK to 1.0 W/mK (NEWMAN, 2005). Conventional concrete has density between 2100 - 2500 kg/m³, compressive strength between 15 MPa and 100 MPa and thermal conductivity ranging from 1.6 W/mK to 1,9 W/mK.

In the production of this material, it is common to use expanded LWA such as Perlite, blast furnace slag, volcanic ash, clays, polymers, among others (CHEN; LIU, 2013) (JITCHAIYAPHUM et al., 2013). When LWC is composed only by coarse aggregate, ie without the presence of the fine aggregate, it is called LWC without fine or low density concrete (BORJA, 2011). Such concrete is characterized by having many interstitial voids, which results in a decrease in density. The voids may also be created through gas or foam forming agents added to the fresh concrete mix (in the cement paste). LWC manufactured by this latter method is called cellular concrete (CC). The low density of CC is obtained by replacing partially or totally the small aggregate with air bubbles (JITCHAIYAPHUM et al., 2013). Finally, when the LWC is formed by the substitution of large aggregates by LWA, are called LWA concrete LWAC. Obviously, because they have fewer natural aggregates, their mechanical properties are usually lower when compared to LWC without fines or CC. Figure 1 depicts schematic view of the three types of LWC cross sections as mentioned above.



(a) (b) (c)

Figura 1 – The three types of LWC: LWAC (a), CC (b) LWC without fine (c).
Fonte: (MORAVIA, 2007)

Chen et Liu (CHEN; LIU, 2013) explain that, the difficulty is to find a material that meets contradictory requirements, ie: high mechanical strength, in which matter is needed instead of empty space and low thermal and acoustic conductivity for which the presence of void is indispensable.

In the research work developed by Moravia (2007), a comparative study of compressive strength at 3, 7 and 28 days between lightweight concrete produced with expanded clay and conventional concretes was carried out. This last concrete was made from crushed limestone aggregate. In this work, four different mixture with compressive strength estimated at 20 MPa, 25 MPa, 30 MPa and 40MPa were performed. Lightweight concrete showed a reduction of approximately 22% to 28% in compressive strength over conventional concretes. According to the author, this decrease in compressive strength, for concretes produced with expanded clay, is due to the low mechanical strength of this type of aggregate.

In the last years, EC have been widely used, according to the granulometry and shape, to produce lightweight concretes with good mechanical properties. EC were produced by the rotary oven process at average temperatures of 1100 ºC, using clays as raw material.

In a recent study, Pereira (2008), discussed some aspects about the application of two granulometries of expanded clays in three formulations. The focus was the mechanical properties, aggregate-matrix interface, porosity and chloride ion absorption profile. For the three blends analyzed, the values of compressive strength were observed to be slightly higher than 20 MPa and a decrease of density at least 32%. The high porosity of the EC did not contribute significantly to the penetration of chloride in the concrete. This was attributed to a good adhesion between the aggregate and the cementitious matrix. The author also observed small porosity concretes when compared to the pores of the expanded clay.

The use of LWA in LWC manufacturing are preferably low cost (CHEN; LIU, 2013). Hence, the use of LWA such as polystyrene beads is widely spreading in concrete technology. Polystyrene beads are easily added in the concrete or mortar to obtain LWC of variable densities (BABU; GANESH BABU; TIONG-HUAN, 2006; GANESH BABU; SARADHI BABU, 2004; RANJBAR; MOUSAVI, 2015; SADRMOMTAZI et al., 2012). Expanded polystyrene (EPS) LWA are also referred to as ultralight artificial aggregates (density less than 33 kg/m³), non-absorbent and hydrophobic. The EPS stands out from the other artificial LWA used in the manufacture of LWC because it is more accessible, that is, it is possible to find the material in most regions (CHEN; LIU, 2013).

2.2 STRUCTURAL LIGHTWEIGHT CONCRETE (SLWC)

SLWC has become popular in the world due to the medium to high mechanical strength and low permeability (MORENO et al., 2014). The density of the concrete usually ranges from 1600 to 1900 kg/m³ and the compressive strength between 20 and 50 MPa (MORENO et al., 2014). Due to the reduction of the mechanical strength with the change of the aggregates, the SLWC hardly present compressive strength above 55 MPa. However, the values of the properties presented are appropriate for most civil works, which has encouraged their increasing use. In the production of this concrete, measures are generally taken to maximize mechanical strength such as water reduction with the use of reducing or/and superplasticizing additives, pre-saturation of LWA before mixing and better control in the conditions compacting and cure.

Due to its good thermal and acoustic insulation performance, SLWC is indicated to places with high agglomerations of buildings, and soils with low support capacity due to its lower density

In recent years, several researchers have been studying the properties of LWC in the fresh and hardened state. Most studies focus on lightweight self-compacting concrete (SCLWC). The largest amount of research in this area is due to the easy segregation that LWC undergoes when it is normally compacted. The aggregates used in the manufacture of LWC, because they have lower densities, it floatd easily with vibration coming from the densification, thus causing segregation.

SLWC have rheological properties different of the LWC and according to EFNARC (2002), three requirements must be considered: Filling ability; Passing ability and Segregation resistance. Several researchers have investigated the properties of SCLWC, some works are cited below.

Güneyisi, Geso\Uglu and Booya (2012) Carried out an experimental study of the properties of SLWC made with LWA from fly ash (FA) and silica fume (SF). A total of 9 mixture of SCLWC were fabricated with 0,35 water cement ratio (w/c) with a cement content of 550 kg/m³ including reference concrete (RC). The fresh properties of the SCLWC were tested by scattering 500t, scattering diameter, V funnel and L box. A statistical study was also performed on SCLWC with and without mineral additions through GLM-ANOVA. The results indicated that the use of combination of FA and SF together decreases rheological properties except for the L box test. Abouhussien and Hussein (2015), analyzed the fresh and hardened properties of SCLWC made with LWA of slate, metacaulin (MC) and FA. Rheological and mechanical tests were performed with different slate contents, w/c ratio and cement contents. The results showed that it is possible to create SCLWC with good rheological and mechanical characteristics controlling the content of LWA and w/c.

An alternative way of producing lightweight aggregate with low energy consumption is through the method of agglomerating particles of fly ash through the cold process. Normally water (wetting agent) is used as coagulant and lime or Portland cement as binder.

Hwang and Tran (2015), investigated the use of the foamed LWA (FLWA) made with hydrogen peroxide through the cold agglomeration process. The resulting FLWA surfaces were treated to improve performance. Eight (8) types of FLWA were for the coarse aggregate in the production of SCLWC with different FA and Blast Furnace Slag (BFS) contents. The authors performed several tests to evaluate the effects of the foaming agent and the surface treatments on the properties of the cold-bonded FLWA. The results showed that the surface treatment of BFS directly affects the compressive strength of SCLWC and that the cold agglomeration process is a low energy and efficient method of producing LWA.

Properties including compressive strength, ultrasonic pulse velocity, chloride ions penetration, gas permeability, total immersion water absorption and capillary absorption of SCLWC made with FA were evaluated by Güneyisi et al (2015). Mixtures with different contents of FA and SF with 550kg/m3 of cement and w/c of 0.35 were used in the SCLWC production. All 9 mixtures were manufactured including the RC. The results of the tests showed that the incorporation of the mineral additions significantly increases the permeability characteristics. In addition, they observed that the compressive strength of SCLWC with SF was much higher than those of RC. Tran and Hwang (2016) Investigated the durability and engineering properties of SCLWC with FLWA based on international standards. In the research several FLWA contents were used in replacement for the coarse aggregate in the SCLWC manufacturing. The results showed that the SCLWC had a consistency and flowability suitable for use in civil works. It was further observed that by treating the FLWA surface it was possible to improve significantly the compressive strength and dynamic modulus of SCLWC and reduce the drying retraction at advanced ages, chloride permeability and thermal conductivity.

Kaffetzakis and Papanicolaou (2016), investigated the steel adhesion in SCLWC made with pumice. For this purpose, tests were carried out through direct extraction of steel and tests on beams. The experimental parameters included: diameter, rebar bond length and type of additive used in the SCLWC blend. Common SCLWC were also made for comparison purposes. The results showed that most of the concretes presented failures due to the separation of concrete and steel in both tests.

Wasim and Hussain (2015), carried out studies about the corrosion behavior of CC, LWAC and SCLWC submitted to normal and high temperatures through corrosion observation, corrosive potential and gravimetric mass loss. For each of the 6 concretes specimens were fabricated with 3% and 5% of chloride and confined in environmental cameras at 30, 40 and 50 °C. The results indicated after 6 months that CC presented higher corrosion than LWAC and SCLWC. The authors also noted that corrosion was lower for LWAC than for SCLWC for all temperatures.

Polystyrene is a thermoplastic polymeric material. The material is expanded with the aid of steam and expansive agents thereby becoming EPS pearls consisting essentially of 98% air. Currently the product is marketed worldwide. The EPS has been used more and more in civil construction due to its low density and thermal conductivity. These two factors provide quite significant advantages such as: lighter elements; Reducing the weight of structures; Reduction of the cost of transport and assembly and greater thermal comfort. LWC can be obtained by replacing part of the traditional aggregates with granulated EPS. By using this material in the manufacture of LWC it is possible to reduce the density from 100 - 200 kg/m³. However, the use of EPS also significantly reduces the compressive strength, which makes it difficult to manufacture SLWC with densities below 1600 k/m³. Another problem that the researchers have been dealing with is the preparation method, since due to its low density, the EPS floats, thus causing segregation of the concrete. In recent years has been given more attention to sustainability and with this the standards of buildings have appealed much for the best thermal comfort to reduce the energy spent with the environments cooling. With that many systems that consist entirely of EPS, such as wall panels, are now available in the market.

The main problem associated with porous LWA is that they absorb a lot of water from the mixture, which generates a water increase to keep the workability at acceptable levels. The additional water increase results in the need to increase the cement content without any increase in strength. In this case, light non-absorbent aggregates (EPS) may be the solution to work around this problem (RANJBAR; MOUSAVI, 2015). An approximate ratio between the average compressive strength and the cement content is given below in table 1 (ACI 213R-03, 2003).

Table 1 - Relation between cement consumption (kg/m³) approximate and compressive strength for SLWC (ACI 213R-87, 1999)

Compressive strength at 28 days (MPa)	Cement content (Kg/m³)	
	Only LWA	LWA + Sand
17,2	240-305	240-305
20,7	260-335	250-335
27,6	320-395	290-395
34,5	375-450	360-450
41,4	440-550	420-500

Studies have been developed focusing on the use of EPS aggregates in common mortar or concrete for structural and non-structural applications. Many experimental and theoretical studies have been dedicated to LWC with EPS in recent years. These studies have shown that the mechanical properties of EPS concrete can be significantly improved by the addition of steel fibers, active silica, fly ash, or additives to the concrete matrix. Some of these works are mentioned below.

Madandoust et al. (2011), studied the properties of SLWC with EPS. The rheology of the SCLWC was evaluated through the slump, T50, V funnel and L box tests. They evaluated 15 mixtures including different w/c ratio, nano-SiO_2 and EPS content (10%, 15%, 22.5% and 30%). The slump variation over time was also evaluated and predicted with multiple regression equations. The results indicated that blends with a density greater than 1900 kg/m³ (up to 22.5% EPS) met SCLWC requirements with EPS. The addition of nano-SiO_2 decreased the rheological properties of SCLWC. The results showed that the reduction of the w/c ratio showed a slump reduction of up to 6% and an increase in the T50 and V funnel values of 23-29% and 18-48%, respectively. They concluded that the inclusion of EPS in SCLWC increased slump maintenance time. The effects of the use of EPS replacing the aggregate on the strength and durability of SCLWC were investigated by Ranjbar et al.(2015). SCLWC with different w/c contents and EPS (10, 15, 22.5 and 30%) were submitted to two different curing regimes. The properties of durability were evaluated through water absorption, electrical resistivity, air permeability and chloride penetration. The results showed that EPS blends cured through the salt wetting regimen showed better compressive strength. SCLWC with EPS showed low absorption at 90 days and blends with densities above 2000 kg/m³ showed low risk of corrosion being classified as good quality.

Pecce et al. (2015), studied the behavior of the bond between steel and lightweight concrete. In the research, EPS was used in partial replacement of the aggregate. Different mixtures of ordinary concrete (OC) and LWC were tested to investigate the influence of the various parameters on the compressive strength. Finally two mixtures of LWC and one of OC were fabricated to determine the behavior of the bond between steel and concrete. Steel bars (black and zinc) adherence tests were executed in the three manufactured mixtures. The results showed a good performance of concrete EPS bonding, although the correlations between compressive strength, tensile strength and bond strength have to be revised in relation to those used for normal concrete.

Tang et al. (2008), analyzed the reinforcement bonding behavior in LWC, in which part of the normal aggregate was replaced by EPS. The researchers performed several adhesion tests on steel bars and fiberglass reinforced polymer incorporated in LWC. The results showed that the use of EPS reduced the density from 2,325 to 1,435 kg / m³ and the compressive strength from 55 to 9.6 MPa. Although the study compared the bonding of glass fiber reinforced polymer bars to steel bars, it provided very useful information on the use of EPS in LWC. The use of EPS in up to 30% of the volume, reduced density (below 1,650 kg/m³) increased the deformation capacity of the LWC although the strength has reduced considerably.

Chen and Liu (2013) evaluated the effects of the foam contents on the workability, mechanical properties and thermal conductivity LWC with foam of EPS. In the experimental studies, mixtures were prepared by partially replacing EPS beads with foams with a bubble diameter of 25-100μm. The resulting concretes presented densities in the fresh state varied from 400kg/m³ to 800kg/m³. The results showed that the use of foams in controlled contents can considerably improve the workability, resistance and thermal conductivity of the foamed foams with EPS. LWC were created with EPS with densities of 400kg/m³ at 800 kg/m³ with compressive strengths of 3.0 MPa at 13 MPa and thermal conductivities of 0.009 W/mk at 0.25 W/mk. The results also showed through the stress-strain curves that the concrete produced had greater ductility and toughness

Bogas and Cunha (2017), characterized the mechanical and physical behavior non-structural LWC (NSLWC) produced with volcanic slag, aiming application in floors of buildings. For this purpose, the density, thermal conductivity, capillary absorption, compressive and tensile strength, elasticity modulus, shrinkage, abrasion resistance and high temperature behavior of the different fill solutions of the NSLWC were analyzed. Eight mixture of NSLWC, including RC made with EC and EPS were produced in all. The results obtained in the present work demonstrated that the density increased while the resistance to abrasion and conductivity decreased. The slag CLNE showed similar mechanical strength, less shrinkage, higher drilling resistance and better behavior at high temperatures than the conventional NSLWC.

Zhuang et al. (2013), analyzed the use of low and high absorption shale in replacement of the coarse aggregate part in the mechanical properties of LWC. The shales were pre-saturated for 24h and then mixed to the rest of the aggregates in the production of LWC with 0.35 w/c ratio. The study showed that the LWC with high absorption shale showed lower tensile performance than the LWC with low absorption shale and RC.

Karamloo et al. (2016), studied the influence of maximum aggregate size on the fracture and fragility parameters of SCLWC. For this, three-point flexural tests were performed on 84 beams made of different aggregate diameter (9.5, 12.5 and 19 mm) with 0.35 and 0.4 w/c. The results indicated that fracture toughness and ductility increase with increasing of the aggregate diameter in SCLWC.

SIM et al. (2013), evaluated the shape and size of the specimens in the compressive strength of LWC. In all 12 mixture were manufactured, being 9 mixed in laboratory and 3 ready mixes. The results of the tests showed that the piece geometry exerts little influence on the compressive strength of LWC

Zhuang et al (2016), analyzed the effect of LWA on the autogenic shrinkage (initial ages) of LWC through the corrugated tube method. The study revealed that autogenous early-phase retraction included liquid phase and the hardening phase. The results also showed that autogenous retraction is also affected by the compressive strength and the absorption. The study also revealed an increase in strength when LWA are pre-saturated.

Several mixtures high strength LWC (HSLWC) using EC were analyzed by Sajedi and Shafigh (2012). The authors used mineral and chemical additives along with limestone to reduce porosity and increase strength. The properties of the resulting HSLWC were evaluated by mechanical tests. The results showed that limestone significantly improved the mechanical properties of concrete when mixed with EC.

The feasibility of the use of palm clinker in replacement of palm shell in the properties of HSLWC were studied by Ahmmad et al. (2016). Many replacements (25, 50, 75 and 100%) of coarse aggregate were used by palm clinker. The resulting HSLWC were characterized according to Slump, compressive strength, tensile-strain behavior, elasticity modulus and their normalization, ultrasonic pulse velocity and failure modes. The results showed that the replacement of palm shell with clinker significantly improves the mechanical properties of HSLWC.

Yew et al.(2015), have investigated the use of polypropylene fibers (PF) in various proportions and geometries in improving the mechanical properties of HSLWC reinforced with palm fiber. The results demonstrated that the fibers were more effective in increasing strength at advanced ages. The authors also observed an increase in elasticity modulus for all HSLWC and a decrease in flexural strength with increased of PF.

Ambily et al. (2015)**,** analyzed the technical feasibility of using copper slag to replace the fine aggregate in the production of high performance LWC (HPLWC). The studies have shown that it is possible to produce HPLWC with compressive strength higher than 150 MPa with the partial incorporation of copper slag. The results also showed that the total replacement of the sand by copper slag causes a decrease in the strength.

Pinto et al. (2012), evaluated the feasibility of using corn cob (without corn) as LWA in the production of NSLWC. The study evaluated the density, compressive strength and thermal insulation properties. The results showed that the use of the cob as EC is feasible for non-structural purposes.

Islam et al. (2016), investigated the use of solid wastes from the palm oil industry in the mechanical and fresh properties of LWC. In the work the shells and the ash from the combustion in the production of LWC were used. The shells were used instead of the coarse aggregate and ashes in partial replacement of the cement of up to 25%. In all, 6 mixture of LWC were produced with these residues. The results showed that the slump and compaction factor increased with 10% and 15% cement substitution by ash. With increasing levels, they noticed a drop in these properties. The effect of the ashes was minimal in the vebe time and in the incorporated air content. The inclusion of ashes in up to 25% did not detrimentally affect the properties of the fresh LWC, while the use of ashes between 10 and 15% improved the compressive strength. Although there was small effect of the ashes on the elasticity modulus, increasing ash levels led to the reduction of the tensile strength in flexure. The authors also carried out at the end an evaluation of the cost and the eco-efficiency of the resulting concretes. The results showed that the inclusion of 10% of the ash presented an excellent performance in terms of sustainability.

2.3 MINERAL ADITIONS

Mineral additions are pulverulent materials composed basically of minerals silica and alumina (SiO_2 or SiO_2 - Al_2O_3.). Due to its pozzolanic properties, are usually incorporated into concrete or mortar (contents ranging 10% to 100%) for improve and/or change some characteristics. They are classified, according to their physical-chemical action, in three groups (DAL MOLIN, 2005):

a) Pozzolanic material: defined as a siliceous or silico-aluminous material (NBR 12653 (1992). This material by itself, has little or no cementitious property, but in the presence of water, it can react with calcium hydroxide (CH), present in Portland cement, and form compounds with cementitious properties (C-S-H). This phenomenon is called Pozzolanic reaction (pozzolan+ $Ca(OH)_2 \rightarrow CSH$).
b) Cementing material: it does not require CH to form cementitious products. The self-hydration of this material is usually slow, and the amount of cementitious products produced is insufficient for structural application;
c) Filler: fine mineral addition without chemical activity, whose purpose is only to fill empty spaces and act as nucleation points for cement grains hydration.

These additions increase concrete durability significantly by modifying the microstructure of the hydrated cement paste, altering the structure of the pores and grain sizes, promoting a reduction in the capillary porosity. These materials also reduce the hydration heat and consequently, thermal fissures (DAL MOLIN, 2005)(BORJA, 2011).

The mineral additions usually used are waste from industrial and agro-industrial by-products, which are often discarded environment. Pozzolans most widely used is from industrial waste, such as silica fume, fly ash, blast furnace slag and agricultural by-products, such as rice husk ash, among others. By replacing a high-cost material such as Portland cement, it provides economic and environmental advantages. However, the use of pozzolanic materials slows the carbonation rate, thus requiring an appropriate dosage

(BORJA, 2011; DAL MOLIN, 2005).

2.4 PORCELAIN TILE POLISHING RESIDUE (PPR)

The PPR is a byproduct from the polishing step during the fabrication of porcelain tiles. This residue shows sometimes pozzolanic activity as a result of its physicochemical characteristics such as high concentrations of silica and alumina (PELISSER; STEINER; BERNARDIN, 2012). Due its small particle size after polishing the PPR can act as nucleation centers besides its filler effect improving the mechanical strength (PELISSER; STEINER; BERNARDIN, 2012; SILVA, 2012). Many companies that use polishing and grinding operations to produce ceramic tiles generate PPR. In the polishing process, diamond abrasives and silicon carbide are used in automated machines cooled with water. The residue from this process is called PPR.

The PPR contains toxic metals from the manufacturing process being classified as class I and class IIA by NBR 10004 (ABNT, 2004), thus needing a managed disposition. The amount of PPR generated by ceramic industry causes a new cost to the producers of the sector (MARQUES, 2007) and due to the high cost involved in the proper disposal of this waste has often led to it being discarded in the environment.

Brazil is the second largest consumer and world producer of Porcelain (ANFACER, 2015). Studies have shown great potential of PPR application due to the pozzolanic property (ANDREOLA, 2010)(SILVA, 2012).

Souza (2007) studied the mechanical and thermal behavior of concrete produced with PPR, ranging from 10 to 50%. The author observed a change in consistency with the addition of higher levels of PPR, an improvement in thermal properties and 40% more compressive strength.

Rodrigues et al., (2010) carried out studies to verify the use of PPR in the production of mortars. To examine the influence of the partial replacement of the Portland cement with PPR (5,10 and 15%), tests of compressive strength, absorption and of pozzolanic activity were carried out.

Pelisser; Steiner and Bernardin (2012) were conducted tests on cement pastes and mortars using the addition of 10% and 20% (mass) of PR. The results of compressive strength in mortars made up to 56 days showed a significant increase in compressive strength greater than 50%. The result of thermogravimetry shows that Portlandite is consumed by the cement formed by the silica present in the residue to form calcium silicate hydrate and featuring pozzolanic reaction.

Electrochemical tests have been carried out by (BIGNOZZI; BONDUÀ, 2011) on steel reinforced mortar samples, prepared using a 25% PPR based cement and exposed to a 3.5% NaCl solution. The results showed at 28 days through the corrosion resistance and microstructure, better durability performances for PPR based cement than those exhibited by RC.

Although it is a waste that has generated great environmental concern, studies about the use of this material in concrete are still scarce.

2.5 LIMESTONE RESIDUE (LSR)

Limestone is a rock composed basically of the mineral calcite, whose chemical composition is calcium carbonate (SILVA, 2009). Limestone Lime is the main component in the manufacture of cement, lime and ceramic. The material is also use in agriculture as a corrective of acid. LSR is the waste from the mining and processing of the rock limestone. Due to the large quantity produced, generally LSR is discarded in lakes, rivers, highway domains and around mining companies, without any kind of treatment. In Brasil, the production of limestone was a growth of 22% since 2003 to 2008 reaching a total of 107 million tons (SILVA, 2009). The amount of LSR in the miners are in the order of 11% by mass of the total produced (DNPM, 2006).

The incorporation of this non-cement material can improve the amount of cement hydration (TOPÇU; UĞURLU, 2003). The calcium carbonate ($CaCO_3$) presence catalyzed the physical-chemical transformations in the cement hydration, leading to higher hydration levels of tricalcium silicate (C_3S).

Limestone has been used in large scale around the world as filler in Portland cement and concrete because it has no binder properties to be used as cementitious material.

The effect of cement substitution by limestone filler on the steady and transitory rheological behaviors of a fresh self-compacting cement paste has been studied by Rubio-

Hernández; Morales-Alcalde; Gómez-Merino (2013). An absolute rheometer has been used to measure rheological properties. Whereas a small proportion of limestone filler (< 3% w/w) favors the self-compacting behavior, higher concentrations of this additive modify the system to convert it into a conventional paste. The results show that, the microstructure break-down rate parameter slightly increases with the limestone filler concentration. The results also show that, the microstructure build-up rate parameter does not show dependence with the limestone filler concentration.

Ghafoori; Spitek; NajimI (2016), evaluated the influences of limestone powder size and content on compressive strength and transport properties of self-consolidating concrete (SCC). Several SCC mixtures were manufactured with 0.45 and 475 kg/m³ cementitious materials ratio and powder content (cement + fly ash + limestone) respectively. Class F FA was used to replace 20% by weight of cement and limestone powder was replaced 10, 15 and 20% of total cementitious materials. The results revealed that the use of limestone powder improve the compressive strength, voids and transport properties of SCC, especially when the particle size is reduced.

The possibility to produce structural lightweight aggregate concrete (SLWAC) with large amounts reside was investigated by Shafigh et al., 2016). They used materials comprised oil palm shell residue as coarse aggregate, and a high volume (50% and 70%) of type F fly ash, as cement replacement by mass. The mechanical properties were evaluated through compressive strength, splitting tensile and flexural strengths, density, ultrasonic pulse velocity, water absorption, and drying shrinkage. The authors concluded that, all oil palm shell concretes containing high volume fly ash are adequate strength for formwork removal. the use of limestone powder significantly improved the compressive strength at early and later ages.

2.6 TIRE RUBBER RESIDUE (TRR)

Due to the lack of viable alternatives for the large number of used tyres that the modern society produce, the deposition in open-air sites or improper places becomes almost inevitable (MARQUES; CORREIA; DE BRITO, 2013).

Today Brazil has a fleet of 87.3 million vehicles and in the last ten (10) years the country recorded a growth of 119%. TRR are already being used in the construction industry in the manufacture of asphalts and sports floors, road barriers, sound insulation panels and expansion joints (MARQUES; CORREIA; DE BRITO, 2013).

Use of TRR in concrete or mortars considerably reduces the compressive strength which makes it impossible to use them in structural elements (PELISSER et al., 2011). However, the material has been widely used in concretes and mortars for non-structural purposes in which thermal and acoustic insulation properties are desired.

The mechanical properties ecological performances of TRR LWC are investigated by Fantilli, Chiaia and Gorino (2016), and compared with concrete made with expanded clay aggregates. Tests were performed such as compressive strength and three point bending tests were performed for two mixtures, containing or not plastic fibers. The results showed a decrease in resistance with the inclusion of TRR and an improvement in flexion and ductility.

Pelisser et al., (2012) evaluated the reduction of cement consumption without decrease the strength, with use of TRR (replacing the sand) in LWC with metakaolin. The properties were evaluated through the compressive strength, calorimetry and thermal conductivity tests of mortar. The results showed that low cement consumption (486kg/m^3) mortar and concrete (260kg/m^3) were produced. The LWC with TRR showed best thermal properties.

Güneyisi, Gesoğlu and Özturan (2004) use two types of tire rubber, crumb rubber and tire chips, were used as fine and coarse aggregate in the test program about mechanical properties of rubberized concretes with and without SF. Six mixture were reduced with different rubber contents by total aggregate volume. Compressive and splitting tensile strengths, and static elasticity modulus were performed. Test results indicated that there was strength and modulus values loss with the increase of rubber content. The results also showed that the use of SF reduces the loss of improving the mechanical.

Gupta, Chaudhary and Sharma (2014), attempt to utilize TRR as partial replacement for fine aggregate in the form of rubber ash and rubber ash with rubber fibers (combined form) with three w/c ratios. Rheological, mechanical, microstructural and durability properties were evaluated. It has been shown that the shape of particle size of TRR influence on flexural strength. TRR in fiber format showed better properties.

3 MATERIAL AND METHODS

To achieve the proposed objectives, this thesis was divided into two sections. In the first one, a 2^3 factorial design was used to select the concretes with the best density and mechanical properties. The goal of the second section was to reduce the amount of cement per cubic meter in order to reduce production costs and to characterize the concrete that presented better properties. The details of the two previously mentioned steps are shown in figures 2 and 3.

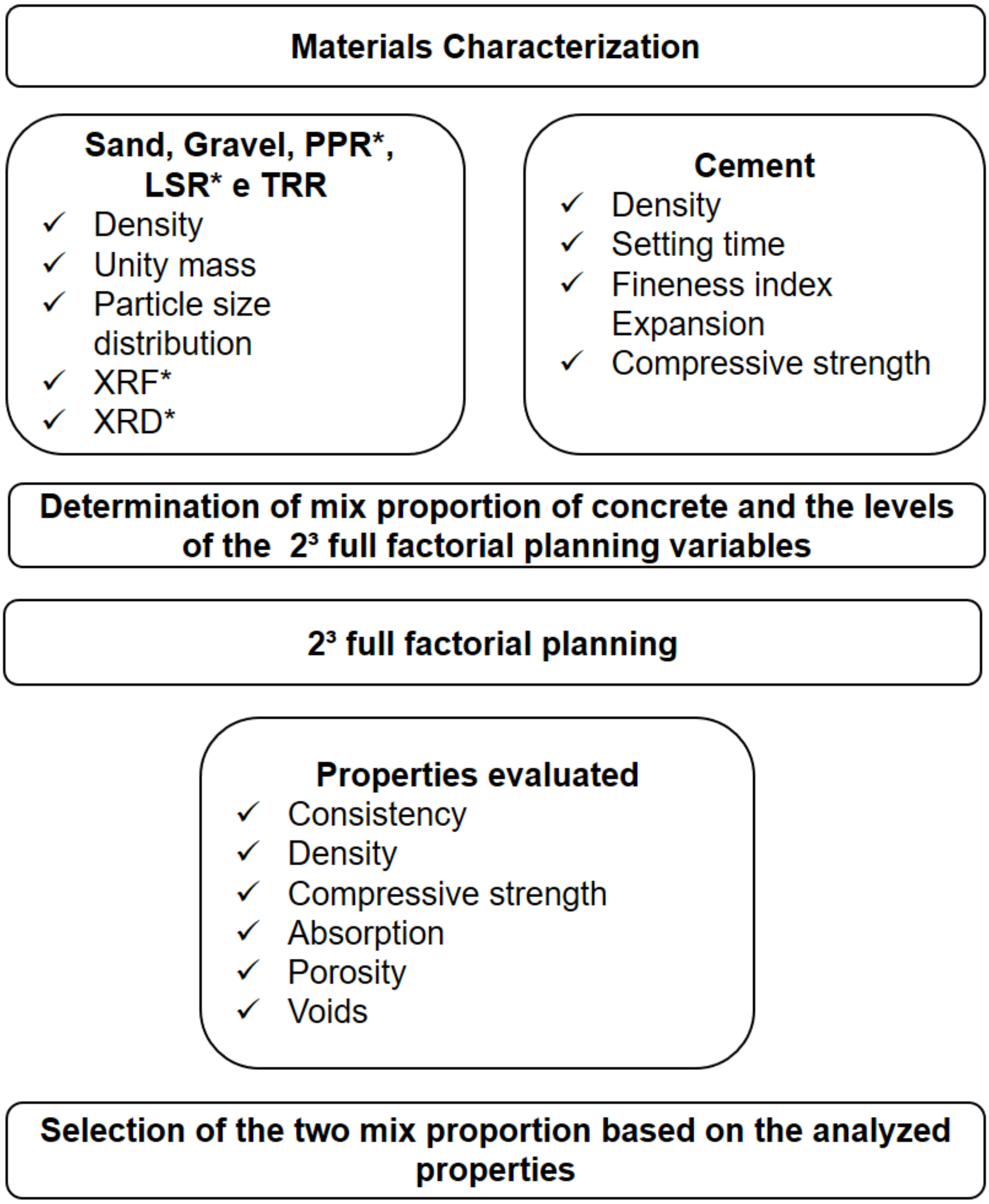


Figure 2 - Organization sequence of the first stage of the thesis.

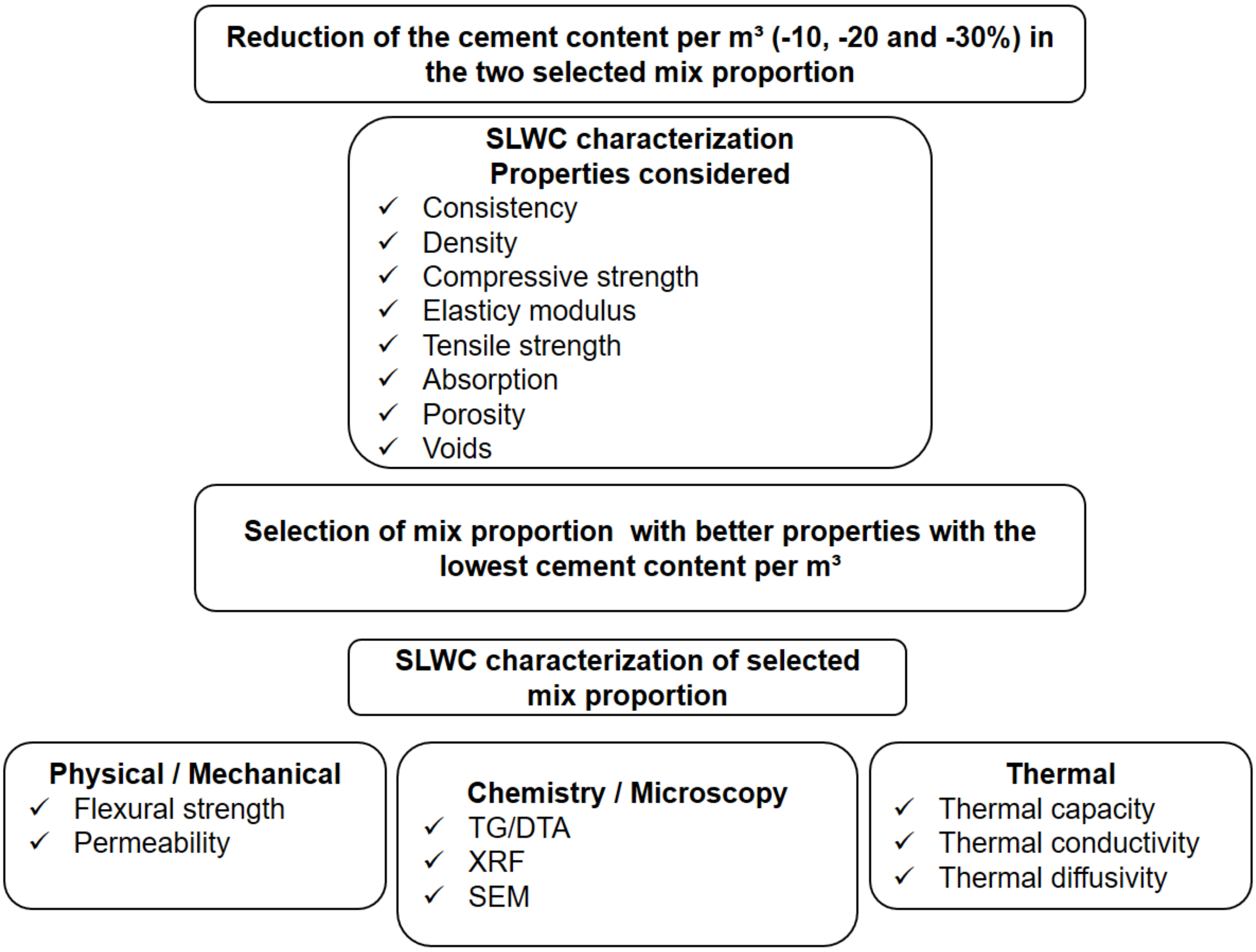


Figure 3 - Organization sequence of the first stage of the thesis.

3.1 FIRST SECTION

3.1.1 Full factorial planning

Initially, a statistical study was carried out to determine the influence of PPR, LSR and TRR on compressive strength and density properties. Compressive strength was selected because it was one of the most important properties of concrete, related to durability and density, to ensure that the concrete produced was light

For the development of the statistical study, it was decided to use the full factorial planning to allow the selection of significant variables in the desired properties, quickly and with a small number of tests. Full factorial planning 2^n was used, in which the index "n" represents the number of variables (residues), which in this case are 3 (2^3). The levels of the variables used (levels of PPR, LSR and TRR) are presented in table 1. The levels exposed were based on preliminary studies and tests.

Table 2 - Levels of residue used in the production of LWC

Variáveis	Lower level	Intermediary %	Higher level
PPR	5	10	15
LSR	4	8	12
TRR	1	3	5

With the determination of the levels of variables (Variation content) it was possible to assemble the planning matrix shown in table 2.

Table 3 - Full factorial planning matrix.

Tests	PPR	LSR (%)	TRR
1	5	4	1
2	15	4	1
3	5	12	1
4	15	12	1
5	5	4	5
6	15	4	5
7	5	12	5
8	15	12	5
9	10	8	3
10	10	8	3
11	10	8	3

The analysis of the influence of the different PPR, LSR and TRR variables on the compressive strength and density of the LWC was performed with the help of the STATISTICA software. All results from the STATISTICA analyzes are showed in annex 1 of this thesis. All of materials used in the production of SLWC were characterized and the results have already been published on article 1

3.2 SECOND SECTION

3.2.1 Selection of the best mixtures

In the second section, two mixtures were chosen that presented the best combination of properties, more relevant to LWC, with the variation of the residue content. For this, the following were considered: the amount of residue; Consistency (workability); Compressive strength and density. The same materials and the same proportion mix used in the first stage of the work were used in the manufacturing of the new lightweight concrete with reduced cement contents per m^3. In the two mixtures chosen, reductions in cement content per cubic meter of 10, 20 and 30% were carried out. These percentages of cement reduction were based on previous studies carried out by the author.

3.2.2 Selection and characterization of the best mixture

After analyzing the results, the best mixture was selected due to properties combination and cement and residue content. The results obtained during this work will be presented in an article format. Article 1 and 2 explain and present the results of the first and second stage of the thesis respectively

4 ARTICLE 1

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Formulação e caracterização de concreto leve estrutural contendo resíduos de polimento de porcelanato, borracha de pneus e calcário

Formulation and characterization of structural lightweight concrete containing residues of porcelain tile polishing, tire rubber and limestone

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RESUMO

O recente aumento da indústria da construção civil transformou concreto em uma escolha ideal para reciclar vários resíduos que anteriormente eram descartados no meio ambiente. Entre os vários produtos, os resíduos de polimento de porcelanato, calcário e borracha de pneus são candidatos potenciais para substituir os agregados miúdos nas misturas convencionais. O objetivo deste estudo foi investigar o efeito da adição de diferentes teores desses resíduos no concreto leve, onde a argila expandida substitui a brita. Para tal, foram realizados ensaios de abatimento, resistência à compressão, densidade, índice de vazios, porosidade e absorção. As densidades de todas as formulações de concreto estudadas foram 10% inferiores às do concreto leve (<1,850 kg / m³). No entanto, misturas contendo 10-15% de resíduos combinados representaram redução da absorção, índice de vazios e porosidade de pelo menos 17% em comparação com o concreto convencional. A resistência de tais formulações atingiu 27 MPa aos 28 dias com consistência de 9-12 cm, indicando uma consistência adequada e um aumento na resistência à compressão. Além disso, a combinação de baixa porosidade, absorção e vazios sugere maior durabilidade ao concreto

Palavras chave: Concreto leve, resíduos de polimento de porcelanato, resíduo de calcário e resíduo de borracha de pneus.

Abstract

The recent increase in the construction industry has transformed concrete into an ideal choice to recycle a number of residues formerly discarded into the environment. Among various products, porcelain tile polishing, limestone and tire rubber residues are potential candidates to replace the fine aggregate of conventional mixtures. The aim of this study was to investigate the effect of the addition of varying contents of these residues in lightweight concrete where expanded clay replaces gravel. To that end, slump, compressive strength, density, void ratio, porosity and absorption tests were carried out. The densities of all concrete formulations studied were 10% lower to that of lightweight concrete (< 1,850 kg/m³). Nevertheless, mixes containing 10 – 15% of combined residues depicted reduced absorption, void ratio and porosity of at least 17% lower compared to conventional concrete. The strength of such formulations reached 27 MPa at 28 days with consistency of 9-12 cm, indicating adequate consistency and increased strength. In addition, the combination of low porosity, absorption and voids suggest improved durability.

Keywords: Lightweight concrete; porcelain tile polishing residue, tire rubber residue, limestone residue.

4.1 - INTRODUCTION

In recent years, concrete has been one of the main forms of recycling of various residues that were once discarded into the environment [1]–[4]. The high energy demand involved in the construction industry [5] and the increasing consumption of concrete have pushed forward recycling initiatives of by-products from various industries [6]–[10].

Aggregates account for 70 to 75% of the weight of concrete, resulting in an annual consumption of 7.5 billion tons. Thus, the use of residues to replace at least a fraction of the aggregates without major effects on the properties of concrete represents a significant improvement in the sustainability of the construction industry [11].

Porcelain tile is a ceramic coating that, as a function of its physical and chemical characteristics, it has been used as an alternative product such as granite and other natural stones. In the porcelain tile manufacturing process, more specifically in the polishing stage, large amounts of porcelain tile polishing residue (PPR) are generated [12]. PPR contains toxic metals from the manufacturing process, thus requiring managed disposal. Nevertheless, the high costs associated with the proper disposal of this waste have made this residue to be frequently discarded into the environment. This practice has caused great social and environmental concern, as Brazil is the world’s second largest porcelain tile consumer and producer [13]. Studies have demonstrated the great application potential of PPR due to both its pozzolanic activity and the filler effect [14], [15].

Studies have also been carried out on residues such as limestone residue (LSR), from the mining and processing of rocks. They are usually discarded in lakes, rivers, roads and around mines. This practice becomes a serious environmental concern when the mines are located around the metropolitan areas [16]. Limestone mainly consists of calcite, i.e., $CaCO_3$ and is used by the construction industry as raw material in the manufacture of lime and cement. It is also used in agriculture as corrective agent for acid soils. LSR can reduce the use of natural aggregates (sand) in the production of concrete. However, literature on this topic is scarce.

Finally, tire rubber residue (TRR) is another material that has undergone a considerable increase due to the worldwide increase in the vehicle fleet [17]. Approximately 1.5 billion tires are manufactured yearly worldwide [18]. TRR is usually disposed on landfills, however, due to its difficult decomposition and considerable reduction of the useful life of landfills with this practice, disposal has proved to be environmentally impracticable [6]. By 2030, roughly 5 billion tires will be discarded yearly without sustainable destination [19]. Several alternatives have already been studied in the construction industry to manage TRR, among which the production of asphalts, sports floors, road barriers, acoustic insulation panels and expansion joints [20]. Although the use of TRR as structural material is not feasible, since it considerably reduces the compressive strength of conventional concrete, researchers have shown great potential of TRR in other areas, especially in vibration damping, impact resistance, fire resistance, thermal insulation on facades, and others [8], [20], [21]. Lightweight concretes have gained wide acceptance in the construction market due to their numerous advantages over conventional concrete, including weight reduction, increase of useful area (due to reduced dimensions of structural parts), low handling costs and transport operations, increased thermal and acoustic insulation and fire resistance [22]. In the production of lightweight concretes, typically some or all the aggregates are replaced by lightweight aggregates including expanded clays, tire rubber residue, pumice, and expanded vermiculite among others, which considerably decreases the density of the material [9]. Concretes with density below 2000 kg/m³ [23] are usually considered lightweight concretes, but ACI 213R-87 [24] defines density ranging from 1400 to 1850 kg/m³.

The replacement of normal aggregates by low-density aggregates in the production of lightweight concrete decreases its compressive strength. The reduced concrete density while maintaining the strength of the material at acceptable levels without increasing the cement consumption (which increases the concrete production costs) is a real challenge. In this sense, the use of by-products to increase volume can be a viable option for the production of low-cost and sustainable lightweight concrete. Expanded clays are traditionally used to replace gravel (coarse aggregate), whereas residues of porcelain tile polishing, tire rubber and limestone can partially replace sand (fine aggregate).

This study evaluated the effect of the addition of different residues (LSR, PPR and TRR) combined with expanded clay in the formulation of lightweight concretes. The resulting compositions were characterized by slump, compressive strength, density, void ratio, porosity and absorption tests.

4.2 - MATERIAL AND METHODS

Portland cement, sand and expanded clay (EC1 and EC2) were used in the production of lightweight concrete. The mix design used was 1: 0.83: 0.875: 0.375 (cement: sand: EC1: EC2). The water to cement ratio was 0.50 with the addition of 1% Glenium SKY 150 superplasticizer by the weight of cement to maintain proper concrete workability. PPR, TRR and LSR residues were added to this mix in different ratios (Table I). In the formulation of the different concrete mixes, a 2^3 full factorial planning was used, with variables in the following levels: PPR 5-15%, LSR 4-12% and TRR 1-5%. Altogether, 9 different concrete mixes were produced and labeled T1 to T9. Three samples were prepared for the central point of the statistical study in order to establish the experimental error. For each mix, different PPR (5, 10 and 15%), LSR (4, 8 and 12%) and TRR (1, 3 and 5%) contents were added. A reference lightweight composition (CP) was also prepared for comparison purposes.

Tabela I: Composição de misturas de concreto leve (kg/m³)
[Table I: Composition of lightweight concrete mixes (kg/m³)]

Concrete mix	Cement	Sand	EC0500	EC1506	PPR	LSR	TRR
CP	535.71	444.64	468.79	200.93	0.00	0.00	0.00
T1	535.71	444.64	468.79	200.93	80.36 (15%)	64.29 (12%)	26.79 (5%)
T2	535.71	444.64	468.79	200.93	53.57 (10%)	42.86 (8%)	16.07 (3%)
T3	535.71	444.64	468.79	200.93	26.79 (5%)	21.43 (4%)	5.36 (1%)
T4	535.71	444.64	468.79	200.93	80.36 (15%)	21.43 (4%)	5.36 (1%)
T5	535.71	444.64	468.79	200.93	26.79 (5%)	64.29 (12%)	5.36 (1%)
T6	535.71	444.64	468.79	200.93	80.36 (15%)	64.29 (12%)	5.36 (1%)
T7	535.71	444.64	468.79	200.93	26.79 (5%)	21.43 (4%)	26.79 (5%)
T8	535.71	444.64	468.79	200.93	80.36 (15%)	21.43 (4%)	26.79 (5%)
T9	535.71	444.64	468.79	200.93	26.79 (5%)	64.29 (12%)	26.79 (5%)

PC II 32 Z RS Portland cement from a single batch was used throughout the study. The cement was subjected to fineness, strength, density, expansion and setting time tests. The cement fineness index was obtained from the material retained in the 75 μm sieve. Cement compressive strength tests were performed using 5 cm (diameter) x 10 cm (height) cylindrical mortar specimens according to current standards. The real density of the cement was determined by the Le Chatelier test, whereas expansion was measured at 7 days using a Le Chatelier needle. The Vicat apparatus was used to establish the cement setting time. The fine aggregate used was clean river sand of coarse grain size (4.8 ≤ d ≤ 2.4 mm).

Two types of expanded clay were used, i.e., 1506 (EC1) and 0500 (EC2) as lightweight aggregate, replacing gravel. All residues used in this work (PPR, TRR and LSR) originated from local industries. TRR and LSR were used as-received in order to address the potential of such residues on large scale. Preliminary sieving was carried out with a 4.8 mm sieve to eliminate large particles and coarse impurities.

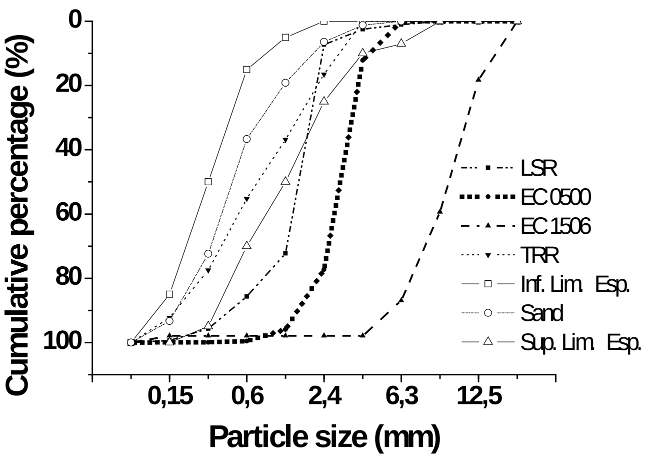
All aggregates (sand, PPR, TRR, LSR and EC) underwent density, unit mass and particle size distribution tests. For the density tests, the Chapman flask was used. The unit mass tests were performed using a 13 L cubic box. Particle size distributions were determined using a set of sieves (4.8, 2.4, 1.2, 0.6, 0.3 and 0.15 mm) and a mechanical stirrer. Selected characteristics of the materials used in the formulation of lightweight concrete are listed in tables II, III and IV, whereas particle size distributions are illustrated in figure 1.

Tabela II: Características selecionadas de cimento, agregados e resíduos.
[Table II: Selected characteristics of cement, aggregates and residues.]

	EC 0500	EC 1506	PPR	LSR	TRR	Sand	Cement
Maximum diameter	6.3	19	-	4.8	4.8	4.8	-
Fineness modulus	4.85	6.47	2.35	2.78	3.6	2.29	1.8
Unity mass	0.64	0.51	1.25	1.55	0.65	1.46	1.42
Density	1.23	0.93	2.60	2.62	0.95	2.63	3.01

Tabela III: Absorção de argila expandida, resistência à compressão e expansibilidade do cimento Portland
[Table III: Absorption of expanded clays, compressive strength and expansibility of Portland cement.]

Time	EC 0500	EC 1506	Cement	
	Absorption		Compressive Strength (MPa)	Expansibility (mm)
15 min	6.95	5.72	-	-
30 min	9.45	8.00	-	-
45 min	10.99	9.24	-	-
60 min	11.05	9.46	-	-
1 day	15.30	13.50	-	-
3 days	-	-	22.57	-
7 days	-	-	29.15	2mm
28 days	-	-	37.92	-



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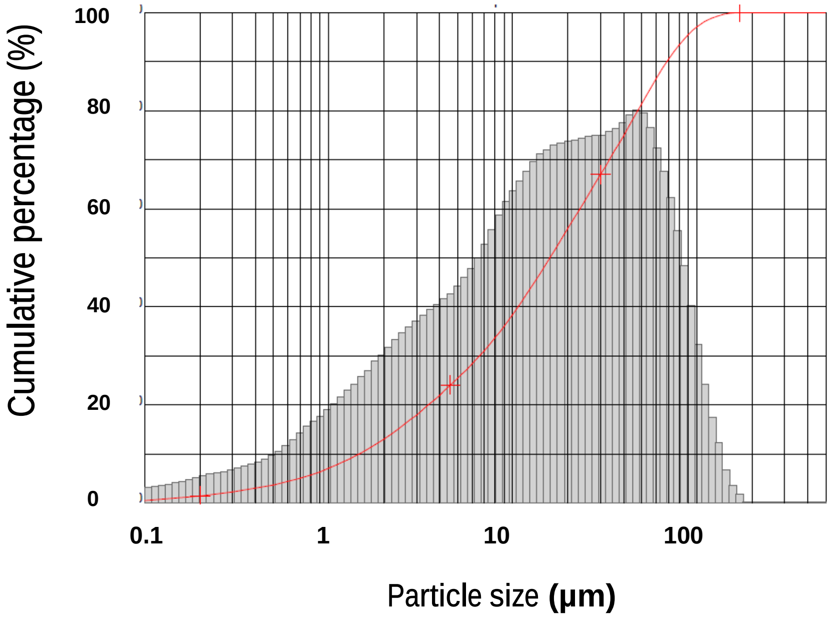


(b)

Figura 1: Distribuição do tamanho de partícula de (a) resíduos e agregados e (b) PPR.
[Figure 1: Particle size distribution of (a) residues and aggregates and (b) PPR]

The chemical characterization of PPR, LSR, EC1 and EC2 aggregates was carried out by X-ray fluorescence (XRF) and X-ray diffraction (XRD). The results are shown in table IV and figure 2, respectively.

Slump tests were carried out only for fresh concrete. To perform the tests, 12 cylindrical specimens of 10 cm (diameter) x 20 cm (height) were prepared for each of the ten mixes studied. After 24 hours at rest, samples were demolded and subjected to immersion cure during 7 and 28 days. After curing, immersion absorption, voids, porosity and density tests took place for each mix using the mass of specimens in the dry, saturated and submerged state. Compressive strength tests in the cylindrical specimens were performed at 7 and 28 days.

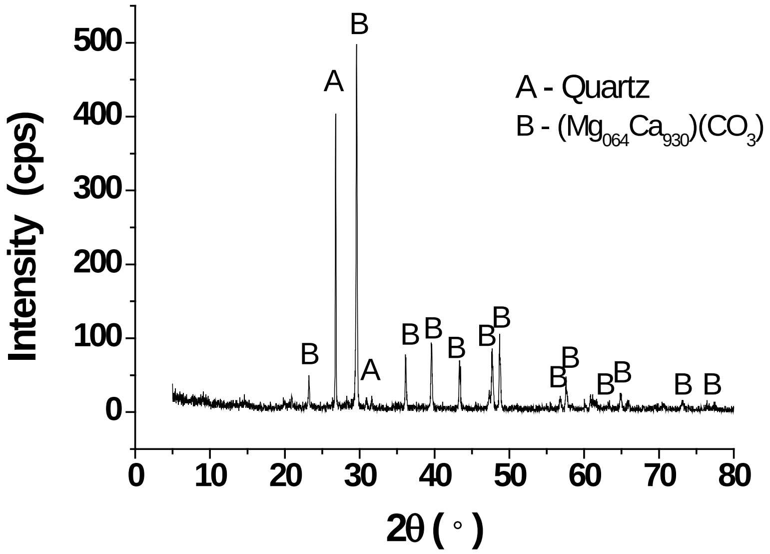
4.3 - RESULTS AND DISCUSSION

LSR consists predominantly of CaO (~76%) in addition to Al_2O_3, SiO_2 and Fe_2O_3. PPR presented as main compounds SiO_2 (71.68%) and Al_2O_3 (18.99%). The chemical analysis also showed very low levels of MgO, K_2O, ZrO2, MnO oxides for both residues. EC1 and EC2 clays, as expected, consist mainly of silicates, aluminates, ferrites and some impurities in the form of K_2O, MgO, TiO_2, CaO and MnO (Table IV).

Chemical analysis by XRD (figure 2) showed that PPR is an amorphous material with some crystalline quartz. Amorphous materials typically have high reactivity with the cement calcium hydroxide (pozzolanic reaction), thereby increasing the compressive strength of hardened material.

Tabela IV: Composição química por FRX dos resíduos.
[Table IV: Chemical composition of residues by XRF]

Oxide	EC0500	EC1506	LSR	PPR
SiO_2	45.89	46.21	8.92	71.68
Fe_2O_3	25.33	24.56	7.35	1.09
Al_2O_3	18.13	18.24	4.08	18.99
K_2O	5.28	5.19	1.34	3.85
MgO	3.04	2.94	0.98	1.40
TiO_2	1.40	1.35	-	0.20
CaO	0.71	0.62	76.64	-
MnO	0.22	0.20	0.15	0.04
ZrO_2	-	0.69	0.51	0.61
Na_2O	-	-	-	1.90
ZnO	-	-	-	0.24



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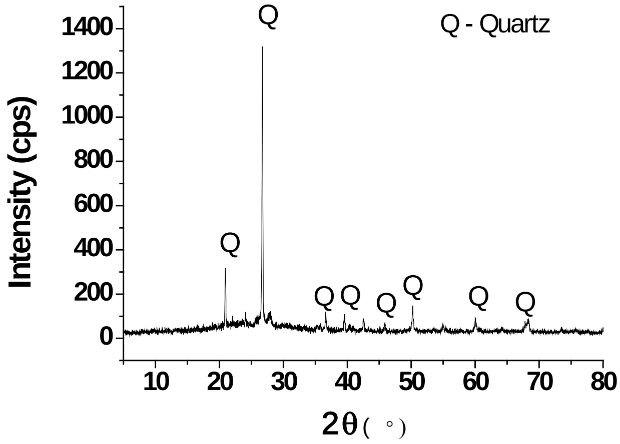

(b)

Figura 2: DRX de (a) LSR e (b) PPR.
[Figure 2: XRD pattern of (a) LSR and (b) PPR.]

Results from slump tests show that the lightweight concrete with residue (LCR) consistency decreases with high PPR and/or LSR contents (Figure 3). Very fine aggregates absorb water, thus reducing the total amount of water required to maintain consistency, which consequently makes the concrete less plastic. This explains why the slump results are lower than those obtained elsewhere [25,26]. Moreover, concretes with medium to low contents of residues (T2, T9, T3 and T7) presented far better consistency when compared to concrete with high PPR and LSR levels (T1, T4, T5, T6 and T8). Concrete T7 showed consistency about 83% better than all other lightweight concrete. The maximum TRR level (5%) used in the production of this concrete and the low amount of PPR (5%) and LSR (4%) significantly contributed to maintain consistency at least 25% higher than that of the other LCR and obtained by Ahmmad et al.

Porosity, absorption and void ratio are properties related to concrete durability. Concretes with low void ratio, absorption and porosity are more compact and waterproof and tend keep service properties for longer times. The results shown in figure 4 show a reduction in the void ratio, porosity and absorption of at least 17% of all LCR in relation to PC concrete. Concretes T2, T5 and T6 showed reduction of almost 40% in porosity in relation to PC and almost 50% when compared with concretes made by Colangelo et al. This behavior can be explained by the filler effect and pozzolanic reaction of PPR with calcium hydroxide (CH). The particle size results in figure 1 and 2 showed large amounts of fine particles that act in the filling of concrete micropores, which characterizes the filler effect. The great amount of silica in the amorphous state of PPR observed by XRD and XRF support the pozzolanic reaction. The combination of the filler effect and the pozzolanic reaction results in less porous and more impermeable concrete. This fact resulted in decreased void ratio, porosity and absorption provided by LCR T2, T5 and T6. The values obtained for the previously mentioned properties are similar to those found in the literature for lightweight concretes [27], [28].

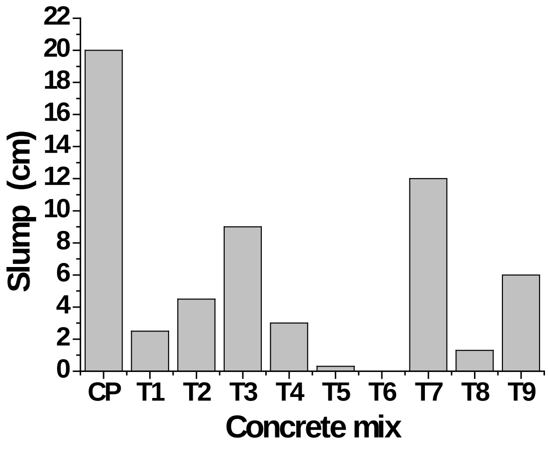

Figura 3: Resultados de abatimento
[Figure 3: Results of slump tests]

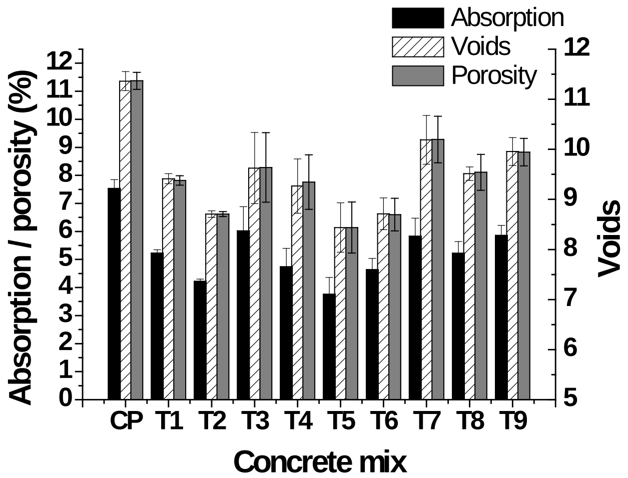

Figura 4: Resultados de absorção, porosidade e vazios.
[Figure 4: Results of absorption, porosity and voids.]

There was no significant variation in density with different sources of residues (Figure 5). All concrete samples produced had density less than 1700 kg/m³. This value is 10% lower than reported elsewhere [25]–[27] and 1,850 kg/m³, which is the density that ACI 213-87R recommends for lightweight concrete and at least 20% lower than those reported for lightweight concrete [29], [30]. The low density of concretes is due to the replacement of normal coarse aggregates of density around 2,600 kg/m³ by EC0500 and EC1506 with densities of 1,230 kg/m³ and 0,930 kg/m³ respectively.

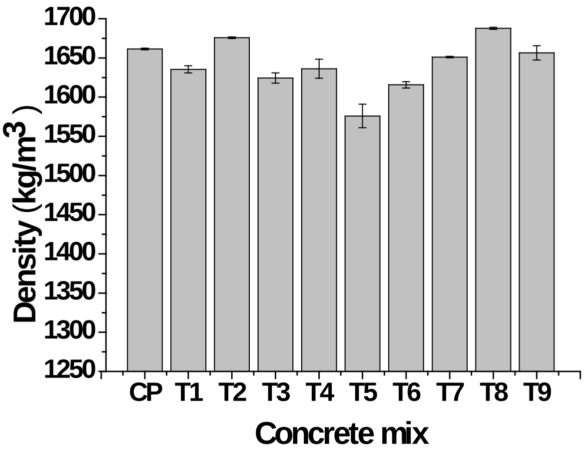

Figura 5: Densidade de misturas de concretos leves.
[Figure 5: Density of lightweight concrete mixes.]

The results illustrated by figure 6 show that the strength at 28 days of all concretes containing residues exceeded that of PC formulation by at least 3%. This result are similar to those reported in the literature [29], [30]. and almost 50% greater than that obtained by Colangelo., et al. The strength of LCR T5 and T6 at 28 days exceeded all others by at least 20%. This increase was probably caused by the low percentage of TRR present. Absorption, porosity and void ratio significantly contributed to the concrete strength. Waterproof and denser concretes tend to have higher strengths. The gain in strength can be explained by both the filler and pozzolanic effects. The reduced strength of T1 compared to the others may have been caused by the high contents of residues present (PPR 15%, LSR 12% and TRR 5%). A relatively slow strength gain to T7 was observed, which showed strength at 7 days nearly 18% less than PC. It is possible that the high TRR content (5%) combined with PPR low and LSR levels (5 and 4% respectively) have contributed to decrease the strength gain at early ages.

Figure 7 shows that the best results were obtained for LCR T3 and T7. These concrete samples showed strength in the order of 27MPa at 28 days with consistency of 9 - 12 cm. Although T5 and T6 have shown better performance in terms of strength, they showed low slump. Consistency is related to the mix fluidity (plasticity degree) and the aspects that most affect this property are the water to dry materials ratio and the characteristics of aggregates such as shape and surface finishing of the particles. PPR and LSR tend to absorb more water due to the large amount of fine particles shown in the grain size distributions of figures 1. The water absorption by these aggregates decreases the amount of water required to maintain consistency, thus making the material drier. LCR T7 showed better consistency due to its low content of PPR (5%), LSR (4%) and also to the higher amount of rubber (5%). The shape of TRR and surface finishing contribute to the improvement of consistency.

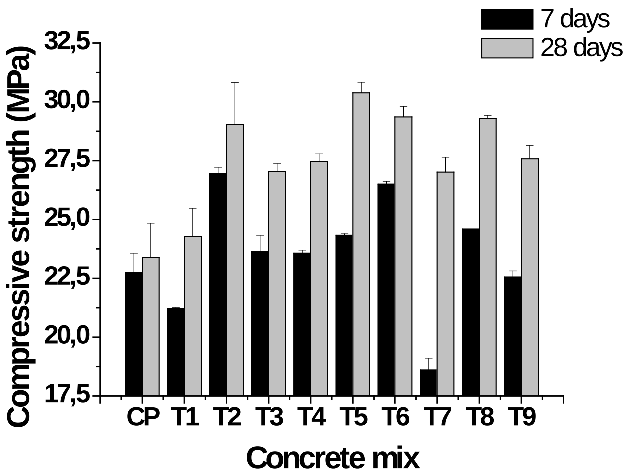

Figura 6: Resistência à compressão aos 7 e 28 dias.
[Figure 6: Compressive strength at 7 and 28 days.]

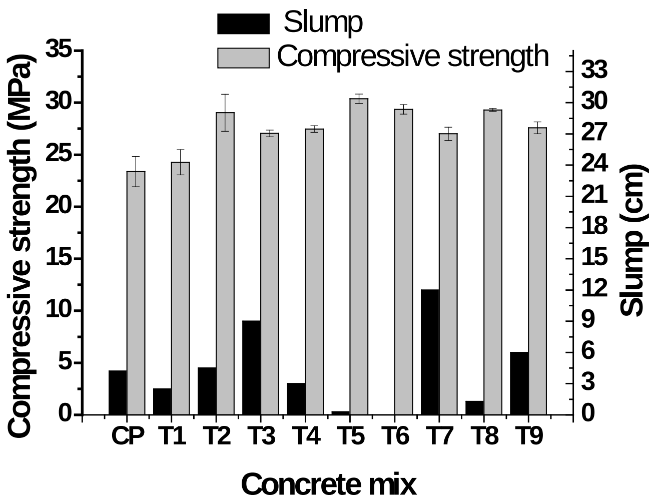

Figura 7: Vista comparativa da resistência à compressão e abatimento de misturas de concretos leves
[Figure 7: Comparative view of compressive strength and slump of lightweight concrete mixes.]

4.4 - CONCLUSIONS

No significant differences in density were observed among the different LCR formulations in the concentration range of PPR, LSR and TRR studied. Formulations with low PPR and LSR levels (5 to 10% and 4 to 8% respectively) and high TRR levels (3 to 5%) showed higher consistencies. Contents from 3 to 5% of rubber reduced the compressive strength and increase consistency. The addition of PPR and LSR improved compactness and compression strength of all LCR, reducing absorption, void ratio and porosity. The use of PPR, LSR and TRR improve durability related properties, since a significant reduction in characteristics deleterious to concrete permeability were observed along with an improvement in compression strength. The use of these by-products in concretes allowed numerous technical and economic advantages since they improve some concrete properties such as compressive strength, porosity and absorption. The addition of residues in concrete also contributes to sustainability since it reduces the disposal of these products into the environment. The best overall results were obtained for LCR T3 and T7.

-ACKNOWLEDGEMENTS

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5 ARTCLE 2

In submition

Análise das propriedades mecânicas e térmicas de concreto leve estrutural de baixo consumo de cimento com resíduo

Analysis of the mechanical and thermal properties of structural lightweight concrete with low cement consumption with residue

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Resumo

Devido à alta energia envolvida na fabricação de cimento e a quantidade de gás liberado, os pesquisadores tem investigado o uso de materiais alternativos como forma de diminuir o consumo de cimento no concreto. Entre os materiais utilizados para este fim incluem-se os fillers (preenchem os espaços vazios) tais como residuo de polimento de porcelanato (PPR) e de pedra calcária (LSR). Materiais que atuam como filler são eficazes no aumento da impermeabilidade, compacidade, resistência e durabilidade. O resíduo de borracha de pneu (TRR) vem aumentando devido ao aumento mundial na frota de veículo.. Todos estes materiais (PPR, TRR e LSR) são descartados na natureza sem qualquer tipo de tratamento, contribuindo assim para a degradação ambiental. A utilização de subprodutos é uma opção viável para a produção de betão leve estrutural de baixo custo. O concreto leve (LWC) e o LWC estrutural (SLWC) ganharam ampla aceitação na construção, devido aos benefícios estruturais e térmicos que este material oferece. O objetivo deste trabalho é produzir e caracterizar um SLWC com resíduos (PPR, LSR e TRR) com baixo teor de cimento, no qual a argila expandida (EC) substitui o agregado graúdo e parte do miúdo. As composições resultantes foram caracterizadas por slump, resistência à compressão, tração e flexão, densidade, índice de vazios, propriedades térmicas, porosidade, absorção, permeabilidade, XRF, SEM e TG/DTA. Os resultados mostraram que é possível reduzir até 20% de cimento do SLWC sem alterar significativamente as propriedades reológicas e mecânicas. O SLWC com resíduos apresentou melhor consistência, resistência à compressão e propriedades relacionadas à permeabilidade. O uso de resíduo na SLWC aumentou a compacidade e a ligação de pasta agregado.

Palavras chave: Concreto leve; resíduos de polimento de porcelanato; resíduo de calcário e resíduo de borracha de pneus

Abstract

Due to the high energy involved in cement manufacturing and the amount of gas released, researchers have investigated the use of alternatives materials as a way to decrease the consumption of cement in the concrete. Among the materials used for this purpose include the fillers like porcelain tile polishing residue (PPR) and limestone residue (LSR). Fillers materials are effective in increasing impermeability, compactness, strength and durability. Tire rubber residue (TRR) has increased due to the worldwide increase in the vehicle fleet. All these materials (PPR, TRR and LSR) are discarded in nature without any kind of treatment, thus contributing to environmental degradation. The use of by-products be a viable option to produce structural lightweight concrete of low cost and sustainable. Lightweight concrete (LWC) and structural LWC (SLWC) has gained wide acceptance in construction, due to structural and thermals benefits that this material offers. The aim of this paper is to produce and characterize a SLWC with residues (PPR, LSR and TRR) with low cement content, in which the expanded clay (EC) replaces the coarse aggregate and part of fine. The resulting compositions were characterized by slump, compressive strength, tensile and flexural strength, density, void ratio, thermal properties, porosity, absorption, elasticity modulus, XRF, SEM and TG/DTA. The results showed that it is possible to reduce up to 20% of cement of the SLWC without significantly altering the rheological and mechanical properties. SLWC with residues presented better consistency, compressive strength and permeability related properties. The use of residue in SLWC increased compactness and the aggregate paste bond.

Keywords: Lightweight concrete; porcelain tile polishing residue, tire rubber residue, limestone residue.

5.1 - INTRODUCTION

Currently the Portland cement concrete has become the ideal choice for utilization of residues that normally were discarded in the environment without any type of treatment [1]–[3]. Due to the high energy involved in cement manufacturing [4] and the amount of gas released, researchers have investigated the use of alternatives materials as a way to decrease the consumption of cement in concrete [5]–[7]. Among the materials used for this purpose include the fillers like porcelain tile polishing residue (PPR) and limestone residue (LSR). Fillers and pozzolans are effective in increasing impermeability, compactness, strength and durability [7]–[11]. Lightweight concrete (LWC) has gained wide acceptance in construction, due to structural and thermals benefits that this material offers [12]–[15]. With the density around 1120-1900 kg/m³, due to the use of lightweight aggregates replacing the common aggregates and minimum compressive strength of 17MPa [16], the main advantages of structural lightweight concrete (SLWC) are reducing the dead weight of the structure, mechanical strength, fire resistance and acoustic insulation [15], [17], [18].

The significant increase in the use of concrete in the world, has accelerated the consumption of natural resources used in its manufacture. Estimates indicates that per year 7.5 billion tons of natural aggregates, are consumed since 75% of the 70% represent the weight of concrete. The replacement of a part of these materials (natural aggregates) for waste can represent a significant improvement in the sustainability of the construction industry [19].

Porcelain tile is a ceramic coating that, as a function of its physical and chemical characteristics, has been used as alternative coating material, to replace cement and products such as natural stones, granite and other. In the porcelain tile manufacturing process, more specifically in the polishing stage, large amounts of porcelain tile polishing residue (PPR) are generated [20]. PPR contains toxic metals from the manufacturing process, thus requiring special hazardous managed disposal. Nevertheless, the high costs associated with the proper disposal of this waste have made this residue to be frequently discarded into the environment. This practice has caused great social and environmental concern, as Brazil is the world's second largest porcelain tile consumer and producer [21]. Studies have demonstrated the great application potential of PPR due to both its pozzolanic activity and the filler effect [22], [10].

Studies have also been carried out on residues such as limestone residue (LSR) [23]–[27], from the mining and processing of rocks. They are usually discarded in lakes, rivers, roads and around mines. This practice becomes a serious environmental concern when the mines are located around metropolitan areas [23]. Limestone mainly consists of calcite, i.e., $CaCO_3$ and is used by the construction industry as raw material in the manufacture of lime and cement. It is also used in agriculture as corrective agent for acid soils. LSR can reduce the use of natural aggregates (sand) in the production of concrete.

However, literature on this topic (limestone extraction residue for the manufacture of cement, lime and others construction materials) is scarce.

Finally, tire rubber residue (TRR) is another material that has undergone a considerable increase due to the worldwide increase in the vehicle fleet [28]. Approximately 1.5 billion tires are manufactured yearly worldwide [29]. TRR is usually disposed on landfills, however, due to its difficult decomposition and considerable reduction of the useful life of landfills with this practice, disposal has proved to be environmentally impracticable [30]. By 2030, roughly 5 billion tires will be discarded yearly without sustainable destination [31]. Several alternatives have already been studied in the construction industry to manage TRR, among which the production of asphalts, sports floors, road barriers, acoustic insulation panels and expansion joints [32]. Although the use of TRR as structural material is not feasible, since it considerably reduces the compressive strength of conventional concrete, researchers have shown great potential of TRR in other areas, especially in vibration damping, impact resistance, fire resistance, thermal insulation on facades, and others [33], [32], [34].

Reducing the density of the concrete, keeping the resistance of the material to acceptable levels without increasing the consumption of cement (which increases the costs of production of concrete) is a real challenge because the mechanical resistance decreases with the replacement of common aggregates for lightweight aggregates. The use of by-products to replace part of the cement and aggregate or even increase the volume, can be a viable option to produce structural lightweight concrete of low cost and sustainable

The goal is to produce and characterize a SLWC with residues (PPR, LSR and TRR) with low cement content, in which the expanded clay (EC) replaces the coarse aggregate and part of fine. The resulting compositions were characterized by slump, compressive strength, tensile strength, density, void ratio, thermal properties, porosity, absorption, permeability, XRF, XRD, SEM and TG/DTA.

5.2 - MATERIAL AND METHODS

In this present work, two SLWC mix with 535.76 kg/m^3 of cement, previously studied by the author (Article 1), were used to perform cement reduction. These concrete mixes were chosen that presented the best combination of properties, more relevant for lightweight concrete, with variation of the residue content. For this, the following properties were considered: the amount of residue; Consistency (workability); Compressive strength and density.

All the materials used in the CLE production were previously characterized according to the correspondent norms. The details of this characterization were presented in Article 1. The reduced quantities of cement per cubic meter were 10, 20 and 30% and mix proportions are available in the Table I. Lightweight concrete generally consumes more cement than ordinary concrete. To avoid the sudden drop of strength with the decrease of the cement ratio (based in previous studies), it was decided to add 10% silica fume by cement weight, and reduce the amount of water as cement contents are reduced (0,50; 0,45; 0,40). In total 6 concrete mix of SLWC were produced to attend the tests (Table I). The proportion of mixture adopted was also based on previous studies (Article 1).

Tabela I: Composição de concretos estruturais leves (kg/m³)

[Table I: Composition of lightweight concrete mixes (kg/m³)]

Concrete mix	Reduction of cement content (%)	Silica fume	Cement	Sand	EC0500	EC1506	PPR	LSR	TRR
CP	0	53,57	535,71	444.64	468.79	200.93	0	0	0
T1.10	10	46,84	468,43	455,46	455,46	195,22	26,03 (5%)	20,82 (4%)	5,20 (1%)
T1.20	20	41,64	416,38	471,83	471,83	202,23	26,96 (5%)	221,57 (4%)	5,39 (1%)
T1.30	30	37,74	377,43	489,42	489,42	207,77	27,97 (5%)	22,37 (4%)	5,60 (1%)
T2.10	10	45,27	452,72	444.64	440,19	188,67	50,30 (10%)	40,24 (8%)	15,09 (3%)
T2.20	20	43,13	431,35	444.64	455,46	195,22	52,05 (10%)	41,64 (8%)	15,61 (3%)
T2.30	30	39,15	391,50	444.64	471,83	202,23	53,93 (10%)	43,14 (8%)	16.17 (3%)

Fresh concrete was only submitted to slump tests. To perform the tests, 12 cylindrical specimens of 10 cm (diameter) x 20 cm (height). After 24 hours at rest, samples were demolded and submitted to immersion cure during 7 and 28 days. After curing, immersion absorption, voids, porosity, density were carried out for each mix using the mass of specimens in the dry, saturated and submerged state. Compressive strength tests in the cylindrical specimens were performed at 7 and 28 days. Elasticity modulus values were calculated through the compressive strength values (the formula) , tensile strength tests were performed through three-point compression.

Slump tests were carried out only for fresh concrete. To perform the tests, 12 cylindrical specimens of 10 cm (diameter) x 20 cm (height) were prepared for each of the ten mixes studied. After 24 hours at rest, samples were demolded and subjected to immersion cure during 7 and 28 days. After curing, immersion absorption, voids, porosity and density tests were carried out for each mix using the mass of specimens in the dry, saturated and submerged state. Compressive strength tests in the cylindrical specimens were performed at 7 and 28 days. Elasticity modulus was also carried out according to NBR 6118 (ABNT, 2007)

After analyzing the results of the 6 concrete mixtures. One was chosen (TF) because it presented better properties with less amount of cement and higher content of residues. The resulting concrete were characterized by tests of: Flexural strength; TG/DTA; XRF; SEM; Thermal capacity; Thermal conductivity and thermal diffusivity. A reference lightweight concrete composition (CP) was also prepared for comparison purposes.

The thermal tests were performed with the help of the KD2-Pro equipment in which thermal capacity, diffusivity and conductivity properties were measured and for better accuracy of the results, 3 cylindrical specimens (5cm in diameter and 10cm in length) were tested for both SLWC (CP and TF).

5.3 - RESULTS AND DISCUSSION

Figure 1 shows that the concretes with 21% of residues showed better rheological behavior. The results for T2 were at least 37% higher. The T2.30 trait was 175% greater than the T1.30. The best consistency of T2 compared to T1 is due to the presence of greater amount of residues in this material, mainly TRR. The values obtained for all SLWC are similar to those found by other authors [1][19] and are ideal for use in most common civil engineering works.

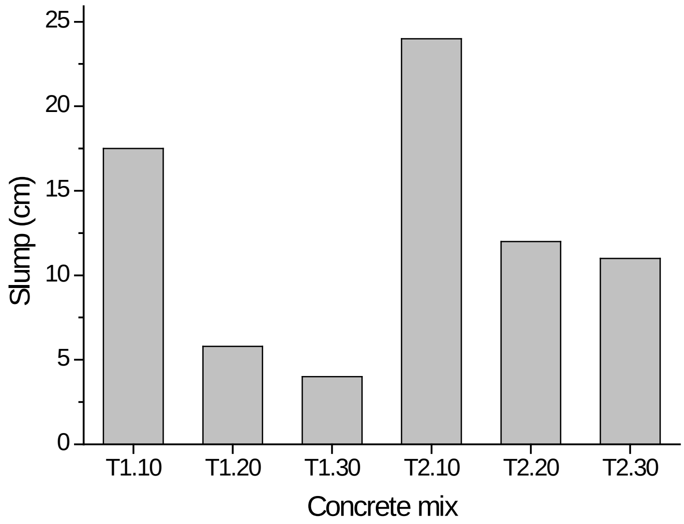


Figura 1: Resultado do slump test.
[Figure 1: Results of slump tests.]

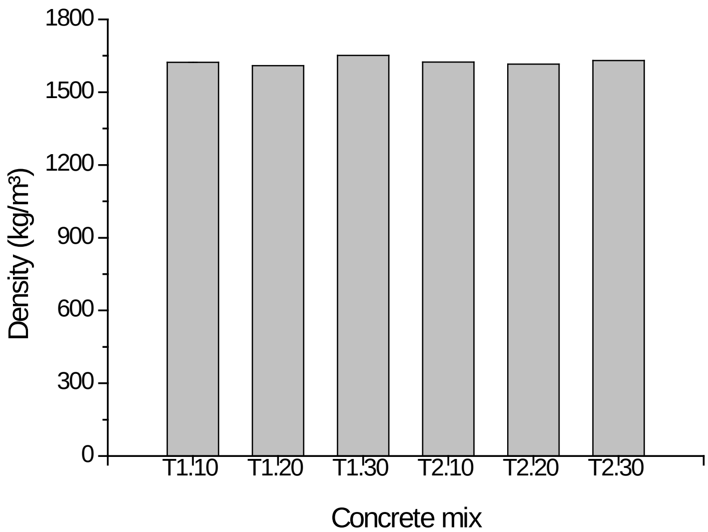


Figura 2: Densidade dos traços de CEL
[Figure 2: Density of lightweight concrete mixes.]

The results shown in Figure 2 that in terms of density, not significant variations with the reduction of the levels of cement were observed. The values presented are 13.5% less than the standard ACI 213R-03 recommends to SLWC and 13% than that presented in the works of [35]. The low density of the concretes is due to replacement of common aggregates (2600 -2700 kg/m ³), for expanded clay (500-1230 kg/m ³). In the SLWC with residue, only the TRR is considered lightweight aggregate, whereas the density of this material was below 1000 kg/m ³ (table II). However, due to the use of the TRR in very low levels, the influence of this material in specific mass reduction was not significant.

By Figure 3 you can see that as the cement content was reducing, there was a decrease in permeability related properties. The decrease of porosity absorption and voids content is due to decreased water cement factor. Concrete with minor's water cement factors usually tend to have smaller voids content, due to smaller amount of water in the mixture, thus reducing absorption, and porosity. The smaller the voids content the less absorption, and porosity because the material will have less empty spaces through which water can flow. The concretes with higher amount of residue (T2) showed almost half the voids content, absorption, and porosity than T1, except for T2.30. The thin size of the residues (see Article 1), coupled with the filler effect of PPR and LSR may have contributed to the decrease of these permeability related properties and durability of concrete. The different behavior of the T2.30 may have been caused by the low amount of cement and higher content of residue 9in the mixture, which resulted in a less SLWC hydration products and consequently greater voids content.

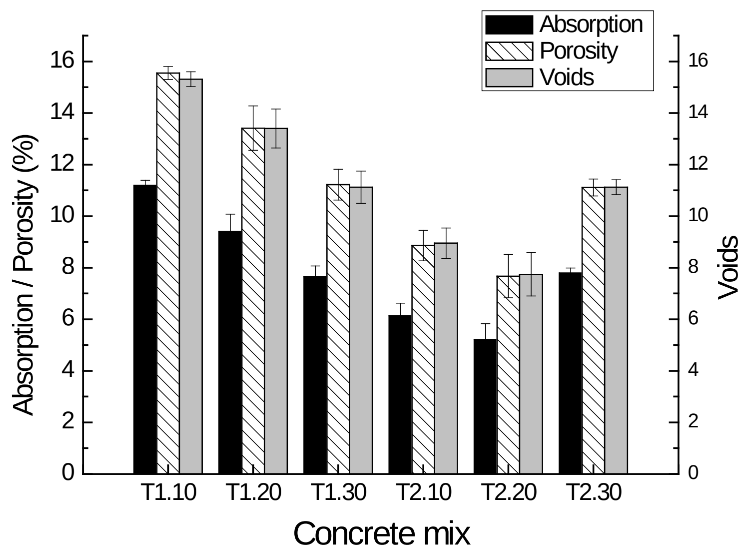


Figura 3: Resultados da absorção, porosidade e índice de vazios.
[Figure 3: Results of absorption, porosity and voids.]

The results of compressive strength in Figure 4 showed that the strength of the SLWC increased with decreasing the amount of cement for all SLWC. The increase of compressive strength observed, was at least 15%. The increase is due to the reduction of water/cement ratio. To 7 days, the T2 (21%) showed a compressive strength of at least 17% greater than the T1, except for T2.30 with a compressive strength 11% below than T1.30. The concrete that featured better strength to 7 days was the T2.20 surpassing the rest with a difference of at least 17% (T1.20) and coming to be 42% greater than the T1.10. At 28 days, the T2 showed again better compressive strength, but the difference between T1 and T2 fell to less than half (minimum of 6.8%). Again, the concrete mix T2.30 did not follow the behavior of the T2.10 and T2.20. Still, the strength obtained for the T2.30 at 7 and 28 days is similar to the values obtained by several authors [1], [24], [36].

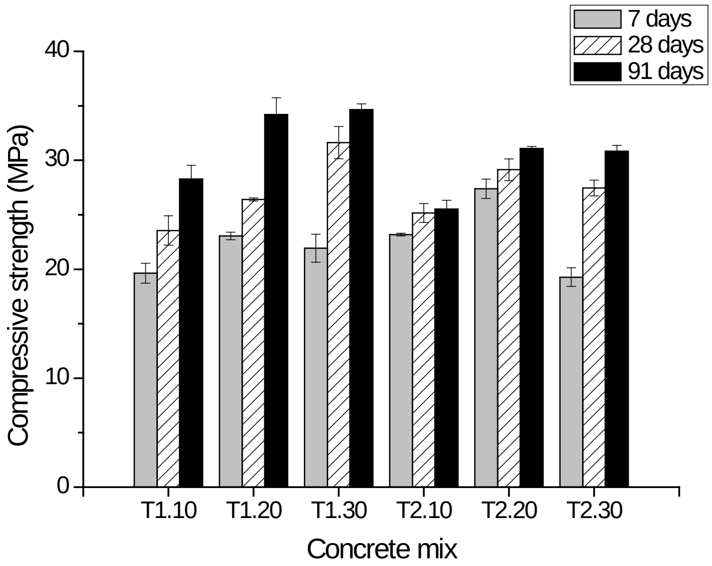


Figura 4: Resistência à compressão aos 7 e 28 dias.
[Figure 4: Compressive strength at 7 and 28 days.]

The T1.30 presented best compressive strength at 28 days (31,63MPa) with a difference of at least 7% (T2.10) and maximum of 31% (T1.10) compared to other concrete mix. The increase of compressive strength of the concrete mix with greater proportion of residue in T2 (21%), could be due to quantity and quality of fine particles of PPR and LSR content and for a better adhesion between cement paste and the lightweight aggregates with decreasing water cement ratio. The amount of fine shown on particle size distribution of those materials (see Article 1) may have served as pore filling material (fillers) contributing to increasing compactness and compressive strength.

The results showed that still 91 days, increasing the compressive strength with reduction in cement content and water was more significant up to 20%. Not observed significant differences in strength at 91 days between T1.20 and T1.30 (34.2 and 34, 6MPa) and not between and T2.20 T2.30 (30.1 and 30, 8MPa). This result could be due to smaller amount of cement present in these concrete mixes. Less cement means less cement hydration reaction and consequently less amount of hydration products formed (CH, C-S-H) which contributing to lower increase of compressive strength.

The least compressive strength of the SLWC to remnants obtained in this study compared to common concrete is due to less compressive strength of lightweight aggregates (EC) used in the replacement part of the aggregates. Another explanation is the low interfacial bond between the lightweight aggregates and cement paste when compared to the common aggregates due to presence of TRR. This fact is confirmed by the analysis of fracture surface of SLWC and the results found elsewhere [28], [29], [34], [37], [38].

The elasticity modulus is the measure of the stiffness of the concrete. The compressive strength exerts a direct influence on this property. Concretes with higher strengths tend to have higher elasticity modulus. In the present work, elasticity modulus followed the same behavior of the compressive strength. However, in general, no significant variations were observed in this property with the variation of cement contents (Figure 5).

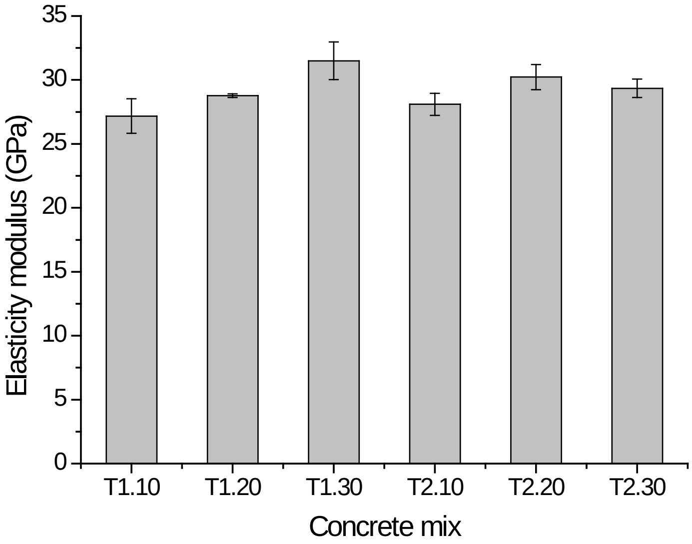


Figura 5: Módulo de elasticidade
[Figure 5: Elasticity modulus]

Figure 6 shows the tensile strength was on average 6% of the compressive strength. The tensile strength of common concrete is typically around 10% of the compressive strength. This difference (4%) in practical terms is not as significant as it is a special concrete. The same justifications presented for compressive strength also apply to the tensile strength.

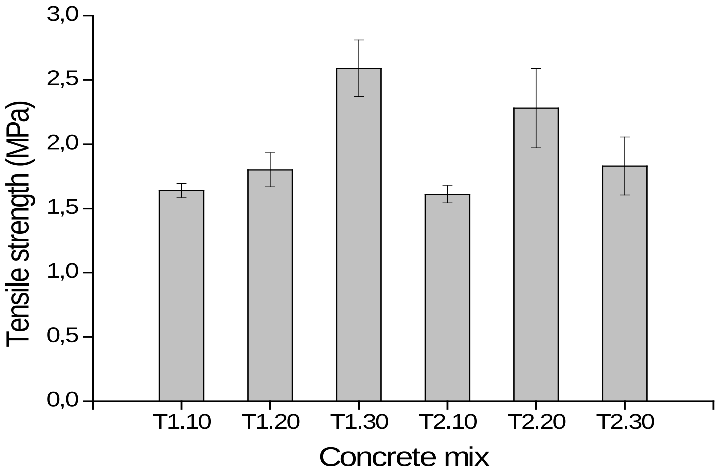


Figura 6: Resistência à tração na flexão aos 28 dias de concretos.
[Figure 6: Tensile strength in Flexural at 28 days of concretes.]

In terms of sustainability the best SLWC was the T2.30 (TF) that presented 27.45 and 30.8 MPa compressive strength at 28 and 91 days respectively. This SLWC was chosen because it consumes the greatest amount of waste with the lower cement content, good workability for most common constructions and the difference of compressive strength to the best features was only 4 MPa for 28 and 91 days. Compared with the 17 MPa limit imposed [16] to be considered lightweight structural concrete, T2.30 presented a 61% higher compressive strength.

The results of figure 7 show that a flexural strength of the TF was not superior to the CP. Such behavior can be caused by the decrease in cement content. The difference is only 32% when compared to CP. Several researchers [24], [39], [40] has demonstrated an increase in flexural strength with the addition of certain materials in concrete. The granulometry of the TRR associated with its long shape, acted as a fiber thus increasing tensile strength. The results of fracture surface and SEM justify this assertion.

The ratio of the amount of heat received by a body to the temperature change is called the thermal capacity. This greatness can also be determined by the product of the mass of the body by its specific heat. In other words, thermal capacity quantifies the heat needed for a body to change its temperature by one unit. Obviously the more insulating the material the greater the thermal capacity. The results of figure 8 show that the TF has a thermal capacity approximately 12% lower than the CP. This observed difference is not significant if we consider the standard error.

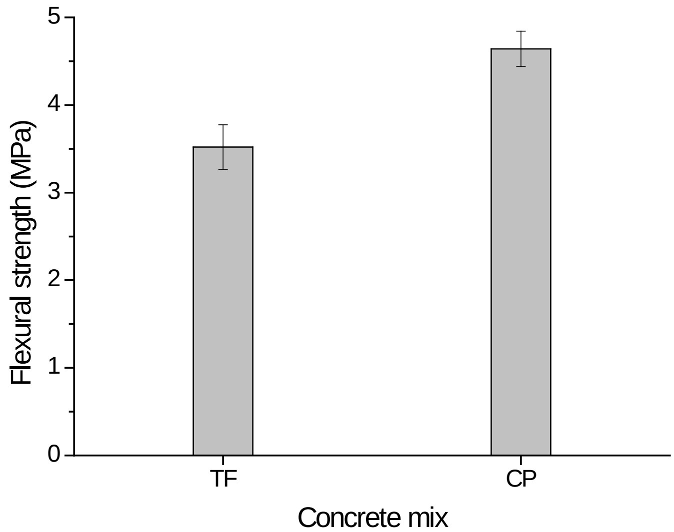


Figura 7: Resistência à flexão aos 28 dias de CP e TF.
[Figure 7: Flexural strength at 28 days of CP and TF.]

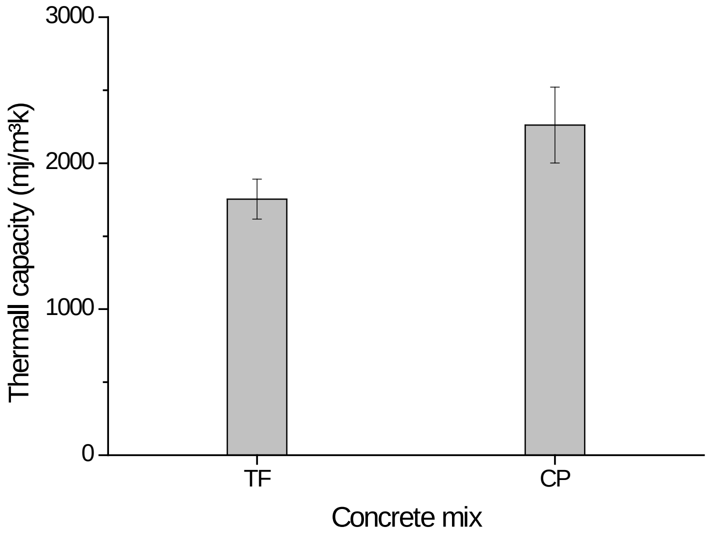


Figura 8: Capacidade térmica do TF e CP
[Figure 8: Thermal capacity of TF and CP]

Thermal conductivity expresses the ability of the material to conduct thermal energy. Materials that have high thermal conductivities (heatsinks) can transmit heat faster than materials with low thermal conductivity (thermal insulation). In figure 9 it was verified that the TF has thermal conductivity only 14% higher than CP. However, in practical terms this difference is considered small.

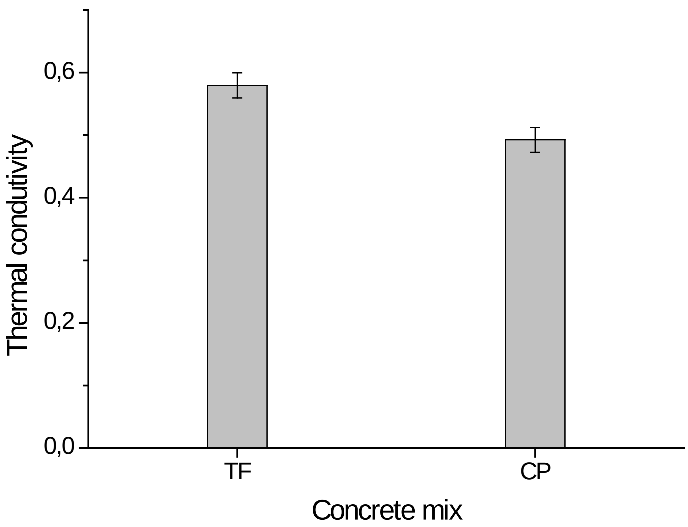


Figura 9: Condutividade elétrica térmica de TF e CP
[Figure 9: Thermal conductivity of TF and CP]

Figure 10 shows that the thermal diffusivity of the TF was higher than the CP around 24%. The low thermal diffusivity means that the material is more insulation, in this way, the concrete mix manufactured has a thermal comfort just below the CP.

The results of the thermal properties showed that the CP is a little more insulating than the TF, this fact may have been caused by the greater number of voids present in this concrete. Normally higher void content of the material means better thermal insulation. Very dense materials tend to be poorly insulated. The addition of residues slightly increased the compactness of the material, as evidenced by the density results (Figure 2), resulting in a slight decrease in the thermal insulation properties observed in figures 8, 9 and 10. The result of the TF similar to the CP is justified due to the TRR present in the concrete that act as insulating material thus hindering the propagation of heat. The porosity, absorption, voids and the amount of silicates and aluminates shown in XRD for the PPR and LSR ally to the polymer microstructure of the TRR justify the behavior of TF.

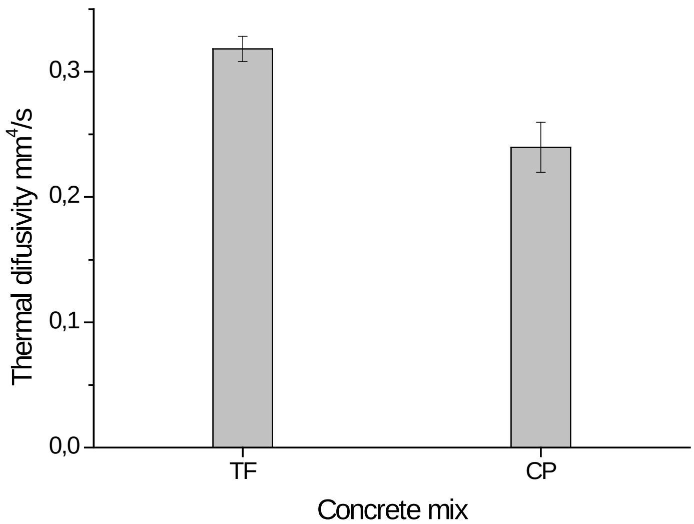
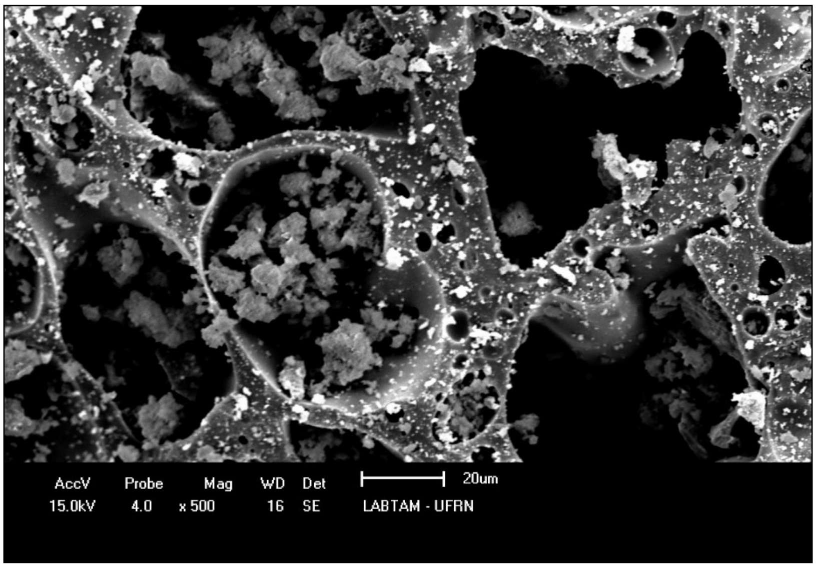


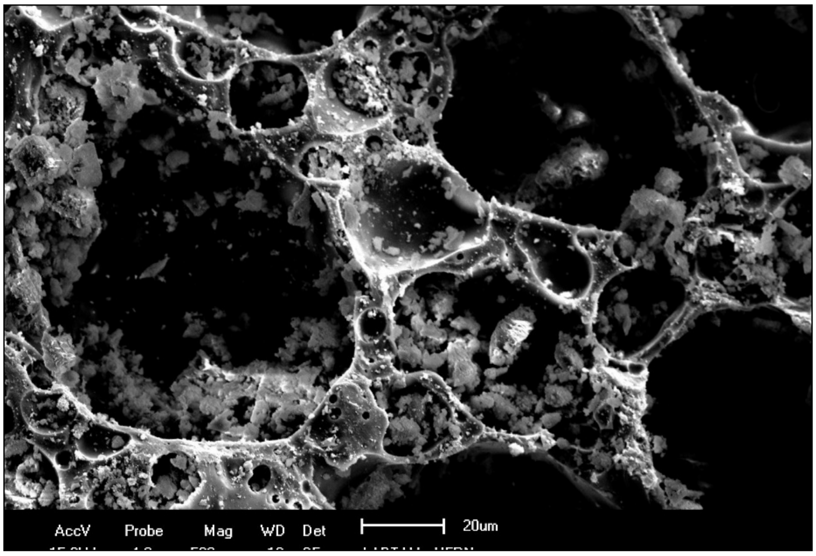
Figura 10: Difusividade térmica de TF e CP
[Figure 10: Thermal diffusivity of TF and CP]

Figure 11 shows the structure of the lightweight aggregate used in the production of SLWC through SEM. Through the image, it is possible to notice that the EC has a very porous microstructure. Porous materials tend to have less mechanical strength, since the pores act as crack propagators, thus accelerating the rupture of the material. This fact is one of the main factors responsible for the low mechanical strength and the increase of the permeability of the SLWC made with lightweight aggregate from thermal expansion. The same conclusions had already been observed elsewhere [41]. Observing the figure 11 it is easy to see that the pores of the TF are more filled than the pores of the CP. This is due to the presence of fine particle size residues (PPR and LSR) that work filling the void spaces of the EC, thus increasing the compactness and impermeability of the material. Figures 12a and b show the cement paste of the SLWC. Looking closely, it is noted that the cement paste of the TF is more uniform and dense than that of CP. The greater compactness of the TF paste is due to the presence of PPR and LSR. Due to the fine granulometry, these materials are more effective in reducing the pore size due to better scattering, filler effect and possibly pozzolanic reaction. The same conclusions had already been observed elsewhere [1], [9].

In images a) and b) of figure 13, the paste aggregate interface of CP and TF respectively is shown. In Figure 13b it is noted that a greater amount of hydration products and a better bond paste aggregate relative to the same region shown in the image of the CP (13a). This behavior was already expected since the concrete has residues in the constitution. The increase of cement paste aggregate bonding is due to the increase of hydration products. more hydration products mean better cement paste aggregate bonding and consequently the better the mechanical strength, since more energy will be required to break the bonds.

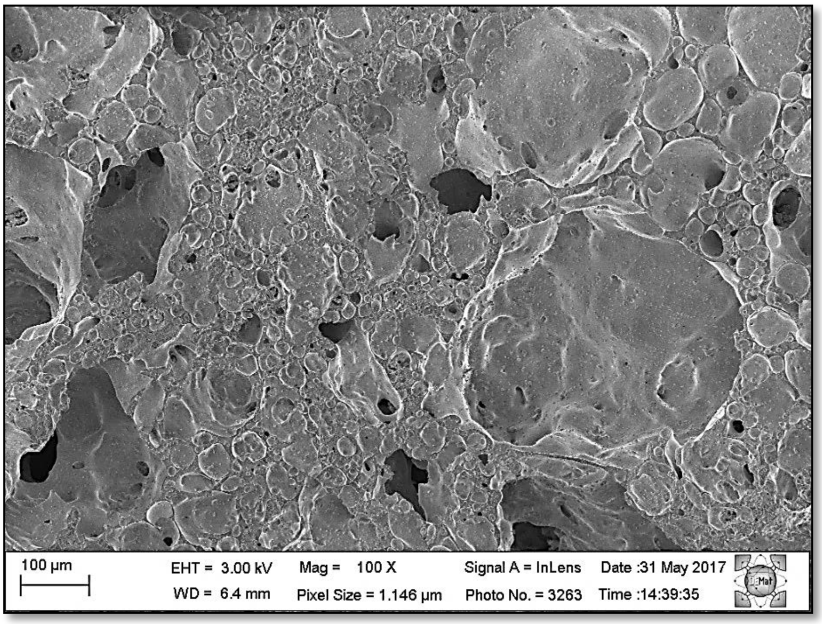


(a)

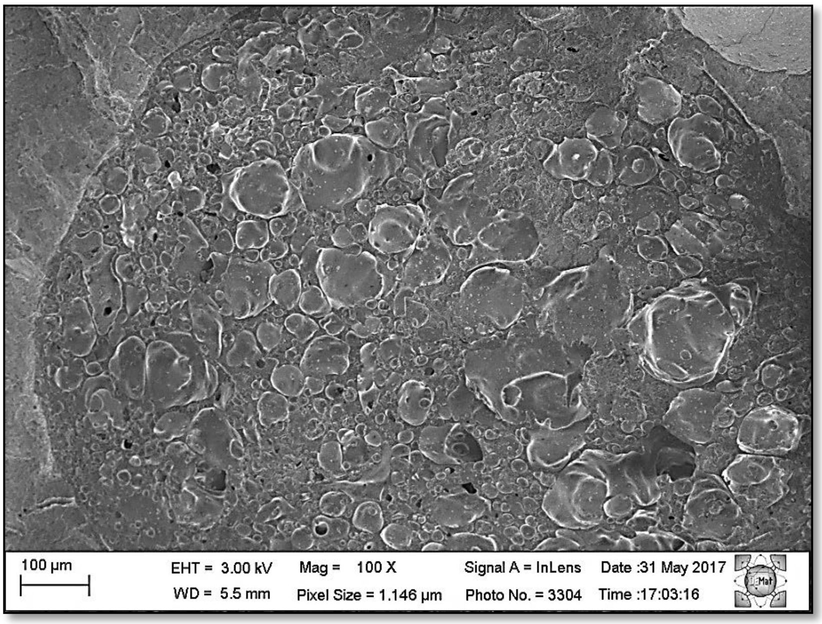


(b)

Figura 11: MEV do agregado poroso CP (a) e (b) TF
[Figure 11: SEM of Porous aggregate (a) CP and (b) TF]

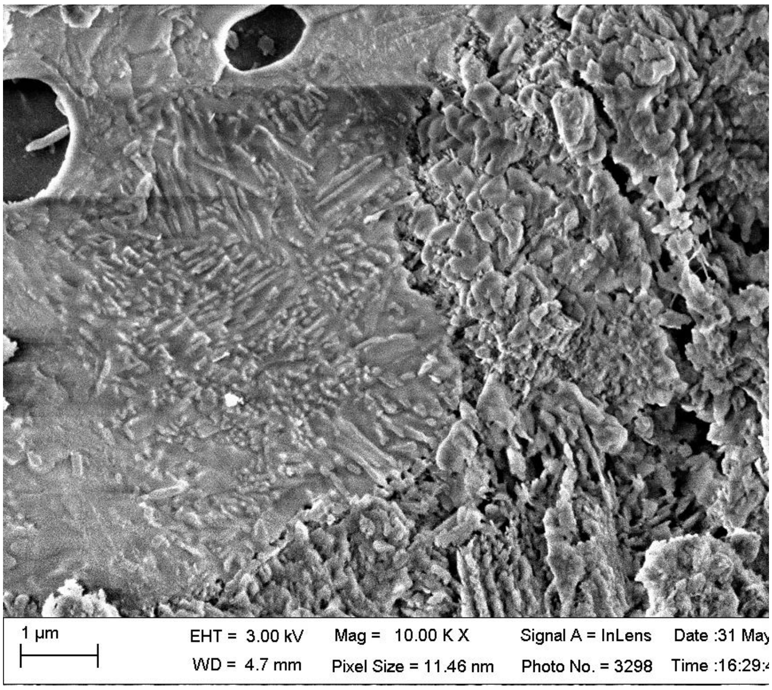


(a)

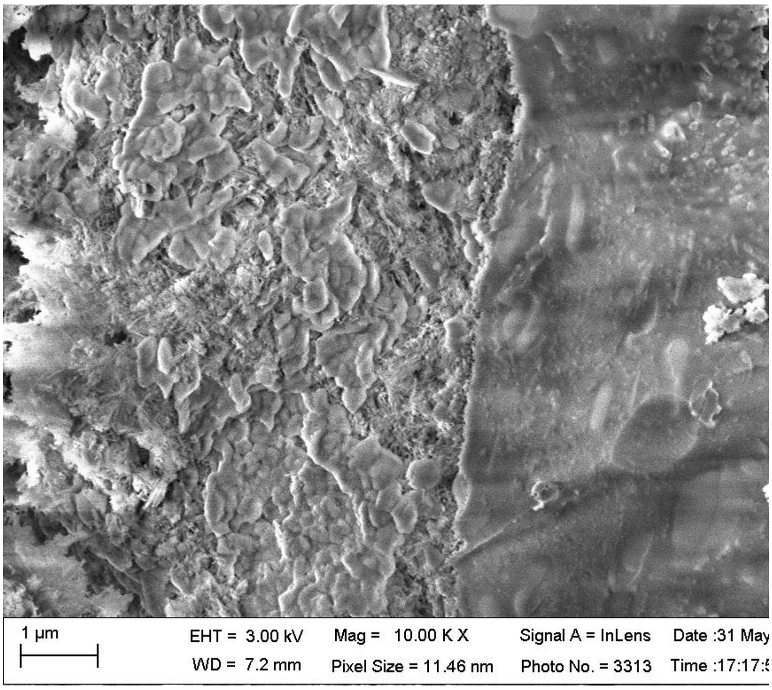


(b)

Figura 12: MEV da pasta de cimento CP (a) e (b) TF
[Figure 12: SEM of cement paste (a) CP and (b) TF]



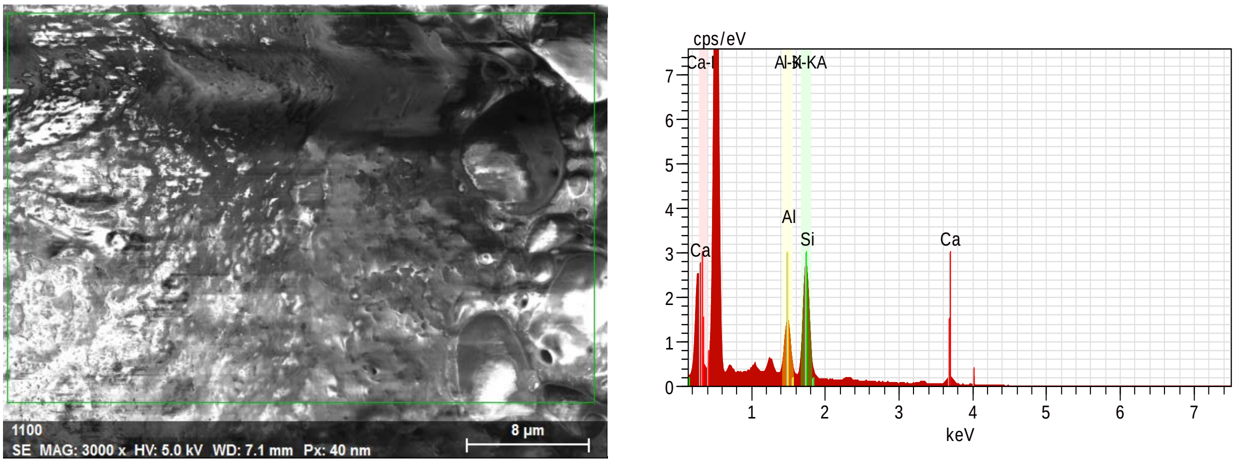
(a)



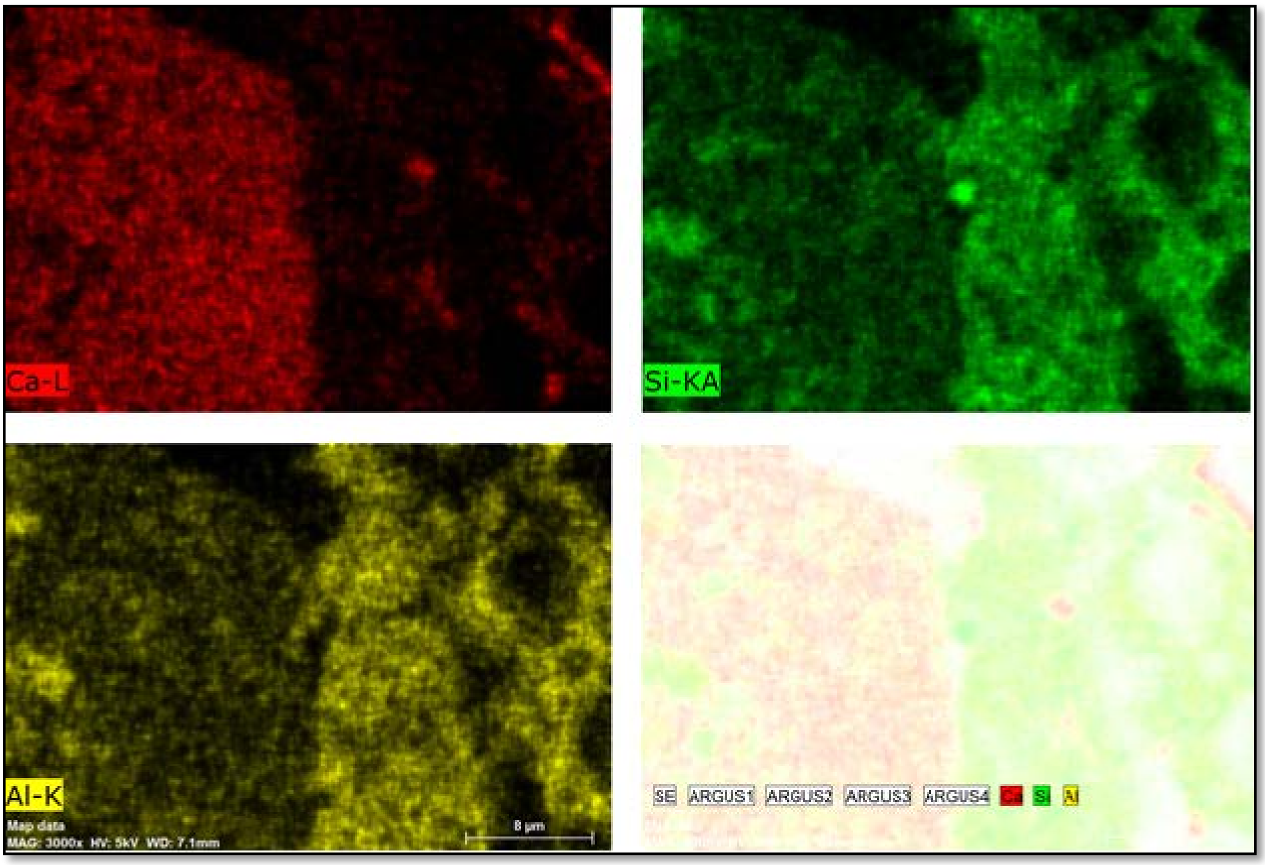
(b)

Figure 13: MEV da ligação Cimento agregado (a) CP e b) TF
Figure 13: SEM of cement paste aggregate bonding (a) CP and b) TF

The proportional distribution of the elements, determined by EDS analysis (Figure 14a), showed that within the TF, Calcium, aluminum and silicon were present. The main components present in the cement and the residues that were used to produce the lightweight concrete. In the images shown in Figure 14b, it is possible to observe the regions corresponding to each element. Through the images it is possible to also notice that the calcium is the element predominant, followed by aluminum and silicon.



(a)

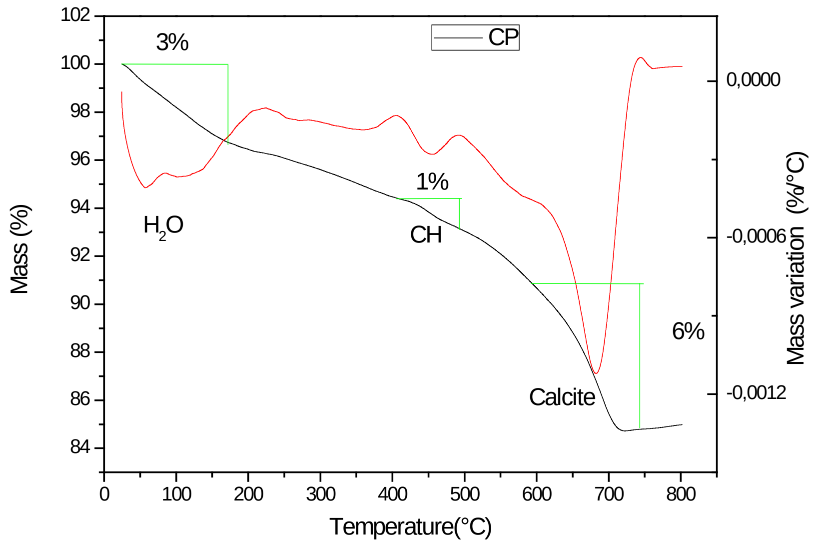


(b)

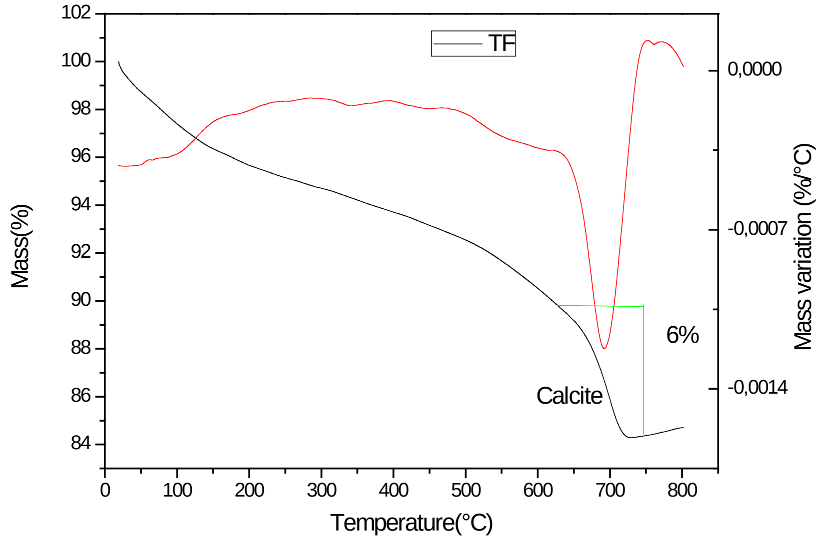
Figura 14: EDS de TF (a) e distribuição dos elementos (b)
[Figure 14: EDS of TF (a) and proportional element distribution (b)]

Observing the dTG curve of figure 15a it is possible to notice that there were 3 mass loss events with CP. The first event, in the range of 0 to 100 ° C, is associated with loss of free water or resulting from the mixture absorption of the paste. The second event, with a temperature between 400 and 500 ° C, with a peak at 450 ° C, is related to the water loss of CH (portlandite). The third and last event, refers to the decarbonation of calcite (CaCO3), that is, CO2 release [42][43].

Comparing the two curves it is possible to note that the amount of mixing water released of CP is higher than the TF, since the material has higher porosity. In the dTG of the TF (figure 15b), it was also observed the decarbonation of calcite at temperatures of 650 to 750 ° C and the absence of Portlandite dehydration. This phenomenon possibly occurred because Portlandite was completely consumed due to the presence of free SiO_2 in the concrete composition. This result was already expected since CP is much more porous than TF. More porous materials tend to retain more water in the constitution. The amount of mixture water release of CP observed in figure 15a and the results of porosity, voids, absorption (figure 3) and thermal properties (figure 8, 9 e 10) suggest the same conclusion.



(a)



(b)

Figura 15: TG/DTA (a) CP e (b) TF
[Figure 15: TG/DTA (a) CP and (b) TF]

The XRF results (Table II) showed a slight advantage for TF in terms of the most important oxides (SiO_2, CaO and Al_2O_3) but in general no significant differences were observed. This fact may have been due to the consumption of oxides in the hydration reaction as suggested by the results of dTG. The same XRF impurities of the aggregates were also observed in LWC XRF.

Tabela II: Composição química por FRX dos concretos leves.
[Table II: Chemical composition of SLWC by XRF]

Oxide	CP	TF
SiO_2	31,79	35,82
CaO	29,47	31,14
Fe_2O_3	17,86	15,10
Al_2O_3	11,80	10,38
K_2O	3,34	3,18
MgO	1,88	1,46
SO_3	1.83	1,33
TiO_2	0.99	0,82
SrO	0.49	0,44
MnO	0,37	0,17
ZnO	0,18	0,16

5.4 - CONCLUSIONS

SLWC with large amount of residues, mainly TRR, tend to present better consistency.

The results of rheological properties found in the present work are compatible with most current uses of civil construction.

The density is not significantly changed with the reduction of the levels of cement.

The porosity, voids and absorption are better with the presence of residues. The permeability related properties are not significantly altered with the reduction of up to 20% of the cement and water.

SLWC with 21% of residue (T2) with up to 20% reduction of cement, presented better compressive strength at 28 days. The increased of compressive strength of the concrete mix with greater proportion of residue (T2), could be due to quantity of fine particles of PPR and LSR and w/c reduction.

The use of residues did not significantly affect the tensile strength but increased the flexural strength.

SLWC with residues (TF) present a difference of thermal properties only 24% compared to SLWC without residue (CP).

The use of residue in SLWC increased compactness and the aggregate paste bond.

The concrete mxi T2.30 (TF) has a 26.3% more efficiency than CP, it consumes less cement and natural source. This SLWC is more sustainable and release less CO_2 in the atmosphere

By end it can be concluded that an economically viable SLWC with good rheological, mechanical and thermal properties was produced with a minimum consumption of cement.

-ACKNOWLEDGEMENTS

The authors would like to acknowledge CAPES-Brazil and PPGCEM-UFRN for the support granted to this work.

6 GENERAL CONCLUSIONS

In the present thesis, it was possible to draw the following general conclusions:

- All the concretes produced with multiple residue showed similar densities, of the order of 1650 kg/m³.
- The addition of TRR contents greater than 3% reduced the compressive strength and increased the consistency of the concretes
- The best consistency was observed with higher levels of TRR (3 to 5%) and lower levels of PPR and LSR (5 to 10% and 4 to 8%, respectively). Even with the reduction of cement per m³ (10, 20 e 30%), the consistencies observed are compatible with most construction works.
- Better mechanical strength was observed for concretes with lower TRR and higher PPR and LSR contents (10 to 15 and 8 to 12, respectively).
- The use of PPR and LSR improved concrete durability since they contribute to the increase of compactness, aggregate paste bond, compressive strength and decrease of permeability. The permeability related properties are not significantly altered with the reduction of up to 20% of the cement and water.
- The thermal properties of the concretes were not significantly affected with the addition of PPR, TRR and LSR.
- In the present work, an ecological SLWC, with good rheological, mechanical and thermal properties was produced with low content of cement and natural resources.
- The addition of waste (TRR, LSR and PPR) in concrete contributes to the economy of natural resources, sustainability and technical advances of the civil construction industry. Reducing the consumption of natural resources, giving an adequate destination to these residues and improving the properties of the concrete.

7 SUGGESTIONS FOR FUTURE WORK

In agreement with the results and the conclusions obtained in the present work the author suggests some studies to deepen the research about SLWC with TRR, LSR and PPR:

- ✓ To analyze the fresh properties of the SLWC with RRT, LSR and PPR;
- ✓ To analyze the durability properties of SLWC with TRR, LSR and PPR;
- ✓ To evaluate the reduction of cement contents without the use of SF;
- ✓ To evaluate the curing conditions of the SLWC in mechanical properties;
- ✓ To evaluate the mechanical and thermal behavior of the SLWC with the use of EPS instead of the EC.

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APPENDIX 1

Table 4 Effect estimates of compressive strength

Factor	Effect Estimates; Var.: Compressive strength ; R-sqr=,89468; Adj:,64892 (zodinio statistica) 2**(3-0) design; MS Pure Error=,0100333 DV: Compressive strength Effect	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	28,11909	0,030201	931,0543	0,000001	27,98915	28,24904	28,11909	0,030201	27,98915	28,24904
(1) Porcelain	-0,40500	0,070828	-5,7180	0,029250	-0,70975	-0,10025	-0,20250	0,035414	-0,35488	-0,05012
(2) Limestone	0,19000	0,070828	2,6825	0,115402	-0,11475	0,49475	0,09500	0,035414	-0,05738	0,24738
(3) Rubber	-1,52500	0,070828	-21,5309	0,002150	-1,82975	-1,22025	-0,76250	0,035414	-0,91488	-0,61012
1 by 2	-1,76000	0,070828	-24,8488	0,001616	-2,06475	-1,45525	-0,88000	0,035414	-1,03238	-0,72762
1 by 3	-0,10500	0,070828	-1,4825	0,276435	-0,40975	0,19975	-0,05250	0,035414	-0,20488	0,09988
2 by 3	-2,42000	0,070828	-34,1671	0,000856	-2,72475	-2,11525	-1,21000	0,035414	-1,36238	-1,05762
1*2*3	-1,04000	0,070828	-14,6834	0,004606	-1,34475	-0,73525	-0,52000	0,035414	-0,67238	-0,36762

Table 5 Regression coefficients of compressive strength

Factor	Regr. Coefficients; Var.:Compressive strength R-sqr=,8946 2**(3-0) design; MS Pure Error=,0100333 DV: Compressive strength Regressn Coeff.	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	28,11909	0,030201	931,0543	0,000001	27,98915	28,24904
(1) Porcelain	-0,20250	0,035414	-5,7180	0,029250	-0,35488	-0,05012
(2) Limestone	0,09500	0,035414	2,6825	0,115402	-0,05738	0,24738
(3) Rubber	-0,76250	0,035414	-21,5309	0,002150	-0,91488	-0,61012
1 by 2	-0,88000	0,035414	-24,8488	0,001616	-1,03238	-0,72762
1 by 3	-0,05250	0,035414	-1,4825	0,276435	-0,20488	0,09988
2 by 3	-1,21000	0,035414	-34,1671	0,000856	-1,36238	-1,05762
1*2*3	-0,52000	0,035414	-14,6834	0,004606	-0,67238	-0,36762

Table 6 ANOVA of compressive strength

Factor	ANOVA; Var.: STRENGTH ; R-sqr=,89132; 2**(3-0) design; MS Pure Error=,0100333 DV: STRENGTH SS	df	MS	F	p
(1) Porcelain	0,32805	1	0,32805	32,696	0,029250
(3) Rubber	4,65125	1	4,65125	463,580	0,002150
1 by 2	6,19520	1	6,19520	617,462	0,001616
2 by 3	11,71280	1	11,71280	1167,389	0,000856
1*2*3	2,16320	1	2,16320	215,601	0,004606
Lack of Fit	3,03432	3	1,01144	100,808	0,009838
Pure Error	0,02007	2	0,01003		
Total SS	28,10489	10			

Table 7 ANOVA of compressive strength of Ftab

Variation source	SS	DF	MS	Fcal	
Regretion	25,050500	5	5,0101	8,201	
Lack of fit	3,03432	3	0,6108		
Pure error	0,02007	2			
Total	28,10489	10			
				Ftab	Ok
				5,05	

Figure 1 Pareto chart of standardized effects of compressive strength

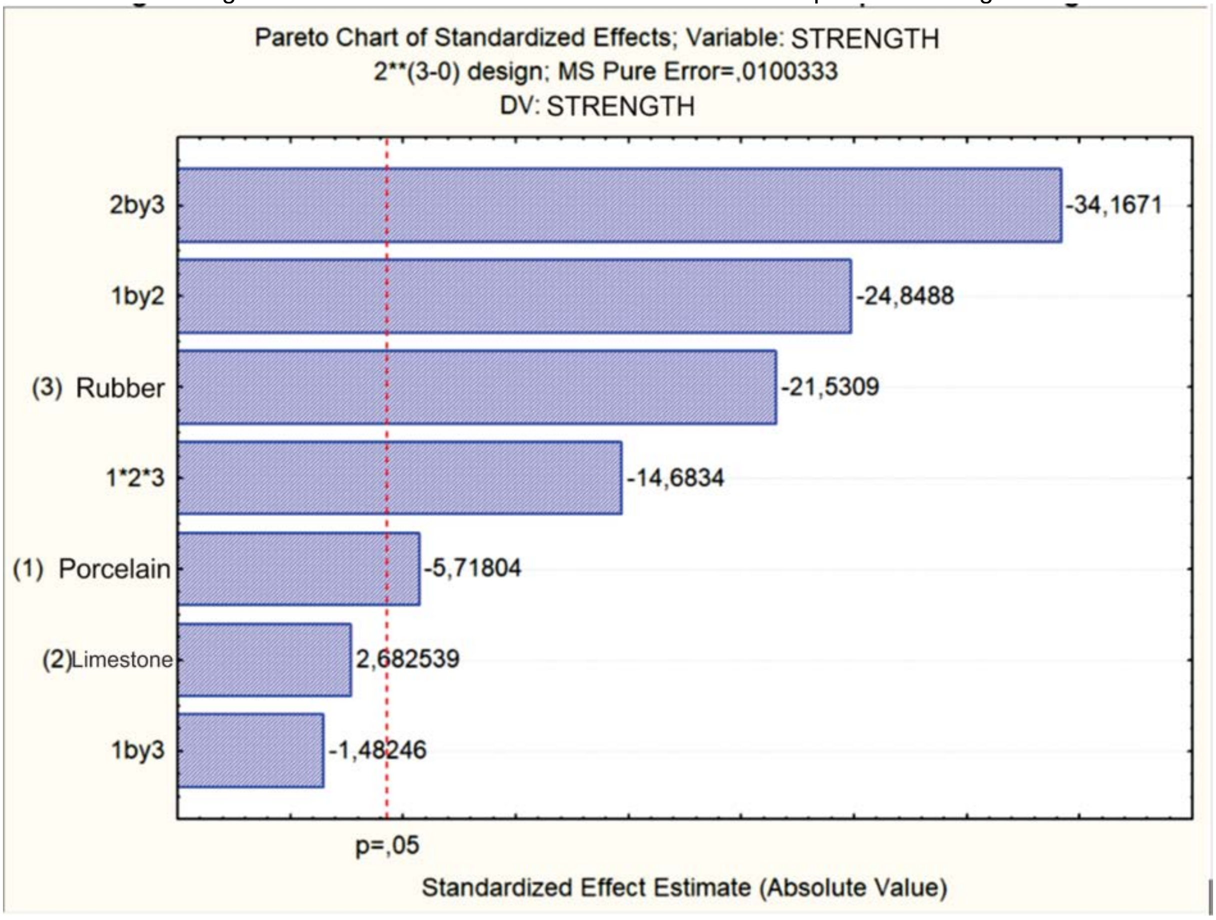

Figure 2 Fiited surface of compressive strength with LSR fixed in -1

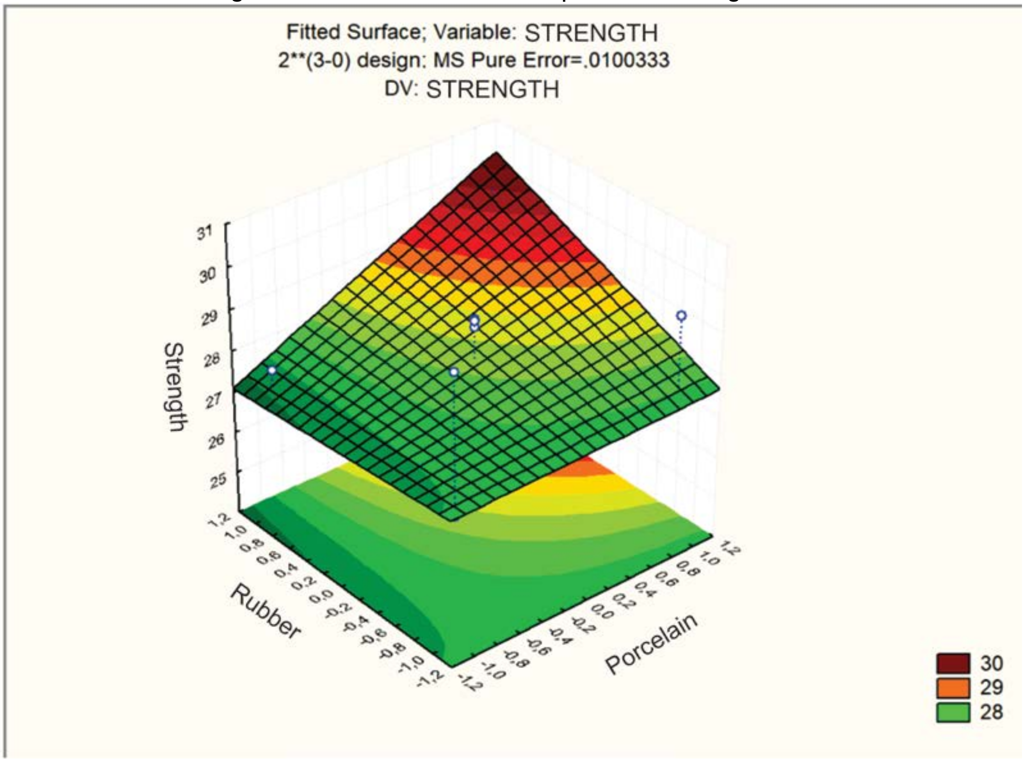

Figure 3 Fiited surface of compressive strength with LSR fixed in 0

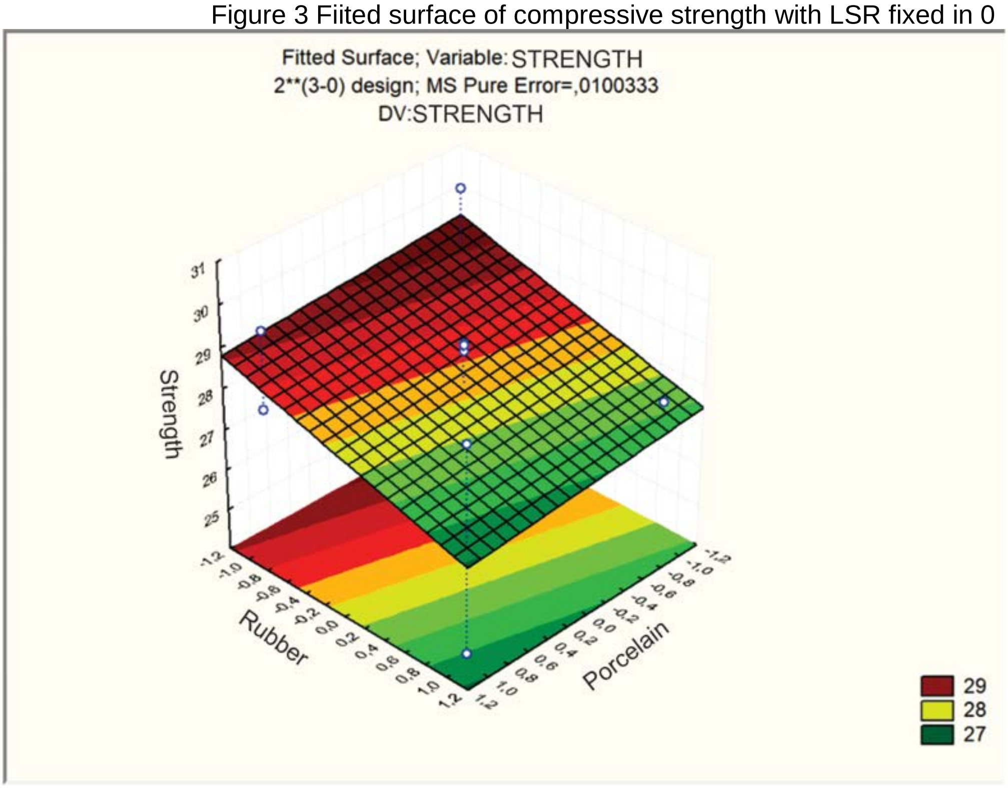

Figure 4 Fiited surface of compressive strength with LSR fixed in +1

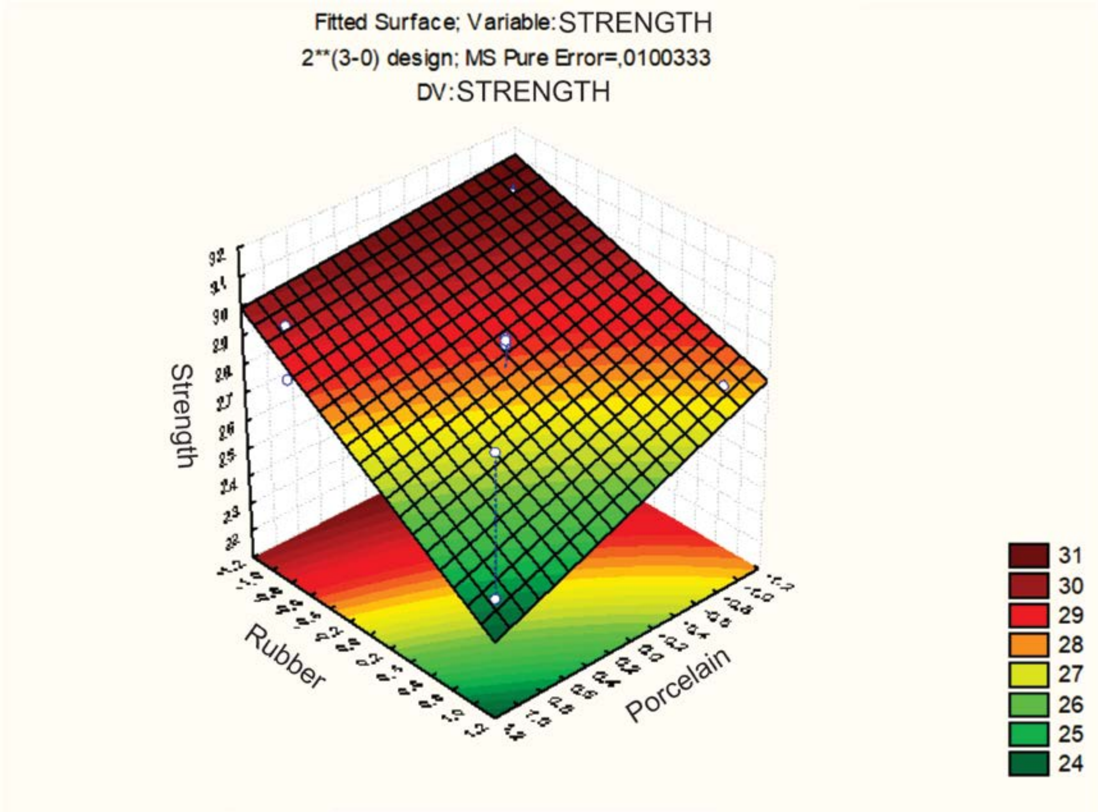

Figure 5 Observed versus predicted values of compressive strength

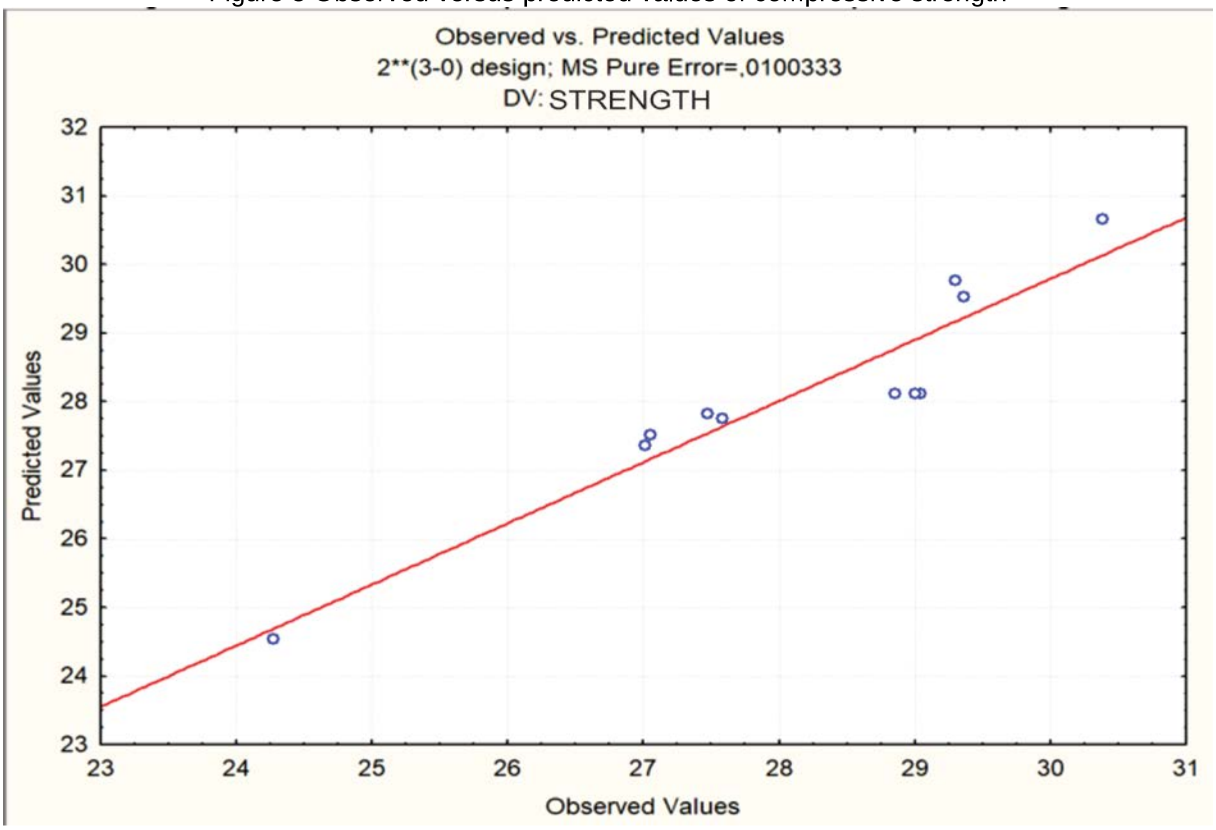

Table 8 Effect estimates of Slump

	Effect Estimates; Var.:Slump; R-sqr=,99935; Adj:,99782 (zodinio statistica Resist in Workbook resist) 2**(3-0) design; MS Pure Error=,0433333 DV: Slump									
Factor	Effect	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	4,26364	0,062765	67,9306	0,000217	3,99358	4,53369	4,26364	0,062765	3,99358	4,53369
(1) Porcelain	-5,12500	0,147196	-34,8175	0,000824	-5,75833	-4,49167	-2,56250	0,073598	-2,87917	-2,24583
(2) Limestone	-4,12500	0,147196	-28,0239	0,001271	-4,75833	-3,49167	-2,06250	0,073598	-2,37917	-1,74583
(3) Rubber	2,37500	0,147196	16,1349	0,003819	1,74167	3,00833	1,18750	0,073598	0,87083	1,50417
1 by 2	3,22500	0,147196	21,9096	0,002077	2,59167	3,85833	1,61250	0,073598	1,29583	1,92917
1 by 3	-1,97500	0,147196	-13,4175	0,005509	-2,60833	-1,34167	-0,98750	0,073598	-1,30417	-0,67083
2 by 3	1,72500	0,147196	11,7191	0,007203	1,09167	2,35833	0,86250	0,073598	0,54583	1,17917
1*2*3	0,37500	0,147196	2,5476	0,125678	-0,25833	1,00833	0,18750	0,073598	-0,12917	0,50417

Table 9 Regression coefficients of Slump

	Regr. Coefficients; Var.:Slump; R-sqr=,99723; Adj:,99307 (zodin 2**(3-0) design; MS Pure Error=,0433333 DV: Slump					
Factor	Regressn Coeff.	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	4,26364	0,062765	67,9306	0,000217	3,99358	4,53369
(1) Porcelain	-2,56250	0,073598	-34,8175	0,000824	-2,87917	-2,24583
(2) Limestone	-2,06250	0,073598	-28,0239	0,001271	-2,37917	-1,74583
(3) Rubber	1,18750	0,073598	16,1349	0,003819	0,87083	1,50417
1 by 2	1,61250	0,073598	21,9096	0,002077	1,29583	1,92917
1 by 3	-0,98750	0,073598	-13,4175	0,005509	-1,30417	-0,67083
2 by 3	0,86250	0,073598	11,7191	0,007203	0,54583	1,17917

Table 10 ANOVA of compressive of Slump

	ANOVA; Var.:Slump; R-sqr=,99723; Adj:,9930 2**(3-0) design; MS Pure Error=,0433333 DV: Slump				
Factor	SS	df	MS	F	p
(1)Porcelain	52,5313	1	52,53125	1212,260	0,000824
(2)Limestone	34,0312	1	34,03125	785,337	0,001271
(3)Rubber	11,2813	1	11,28125	260,337	0,003819
1 by 2	20,8013	1	20,80125	480,029	0,002077
1 by 3	7,8013	1	7,80125	180,029	0,005509
2 by 3	5,9513	1	5,95125	137,337	0,007203
Lack of Fit	0,2813	2	0,14064	3,246	0,235536
Pure Error	0,0867	2	0,04333		
Total SS	132,7655	10			

Figure 6 Fiited surface of Slump with LSR fixed in -1

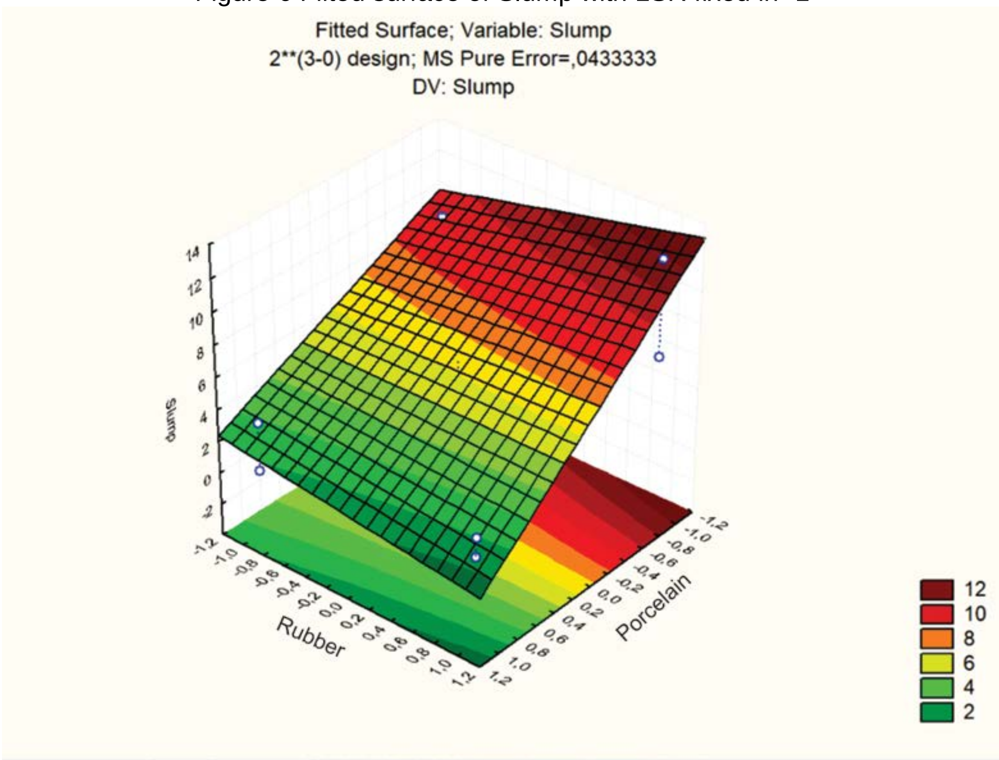

Figure 7 Fiited surface of compressive strength with LSR fixed in 0

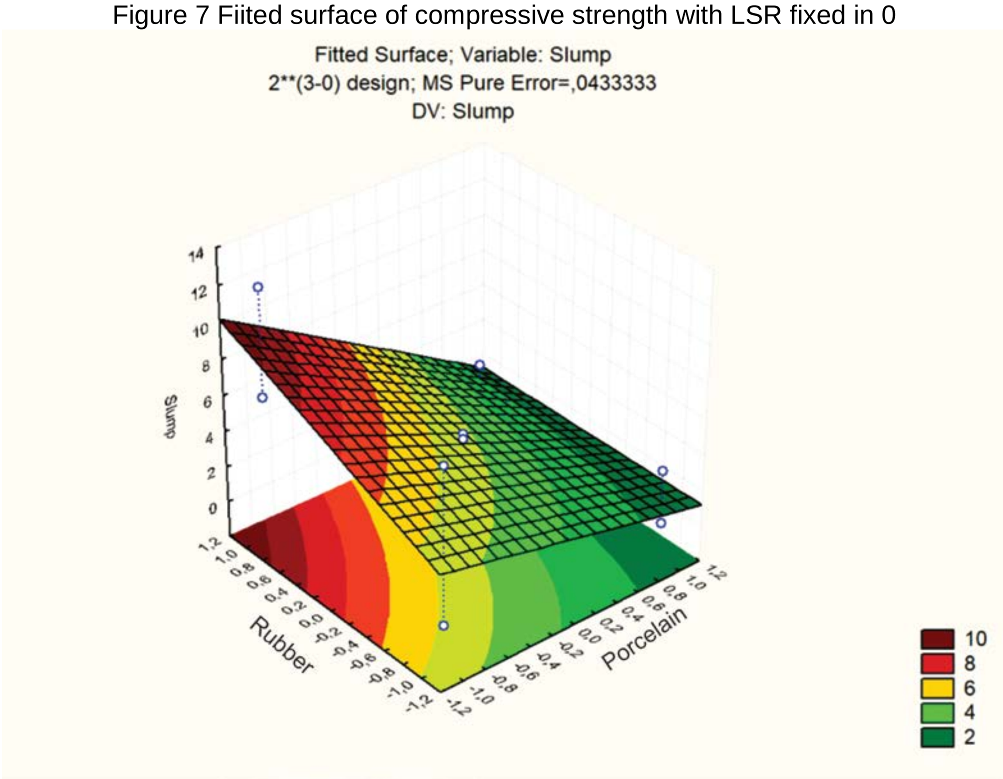

Figure 8 Fiited surface of Slump with LSR fixed in +1

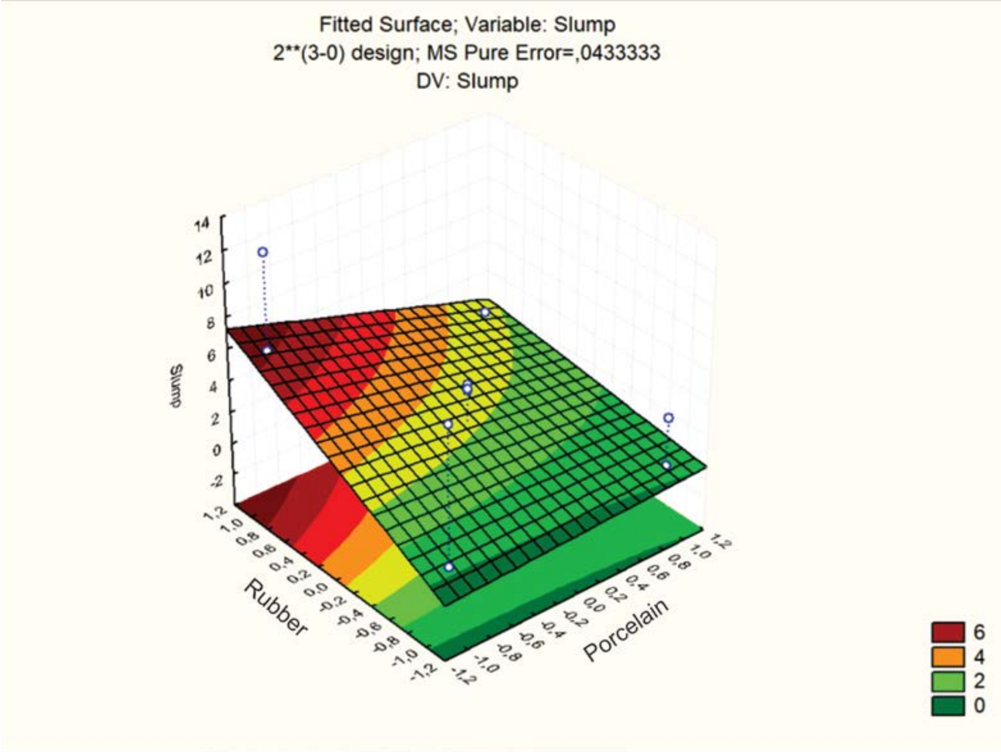

Figure 9 Fiited surface of Slump with TRR fixed in -1

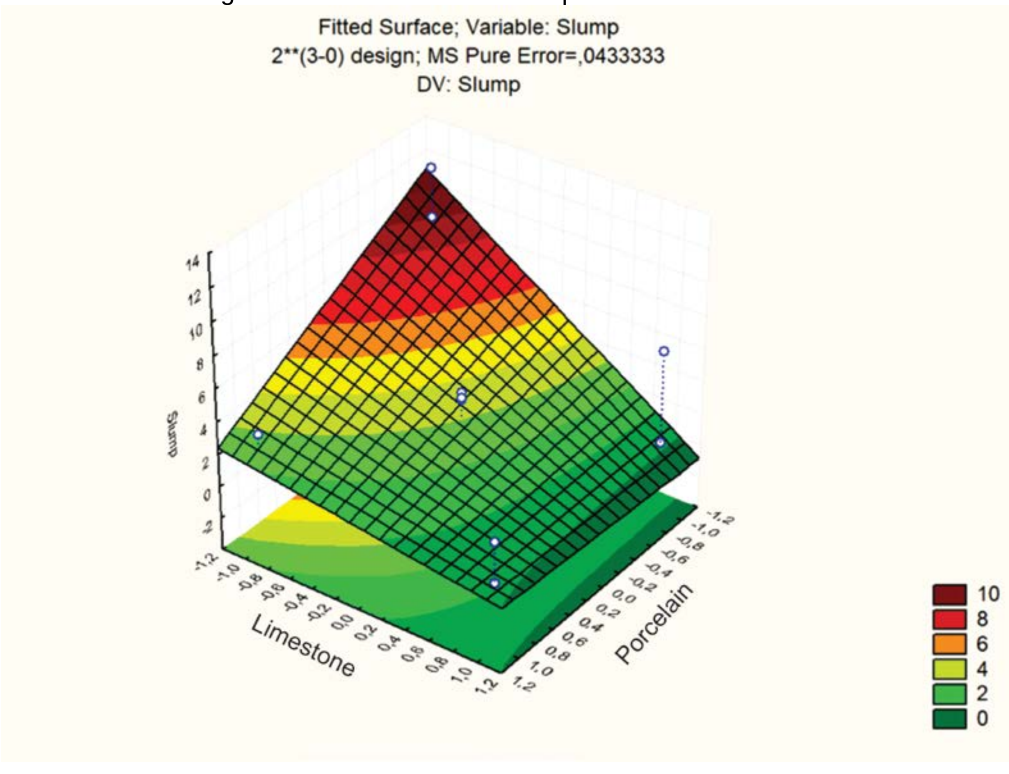

Figure 10 Fiited surface of Slump with TRR fixed in 0

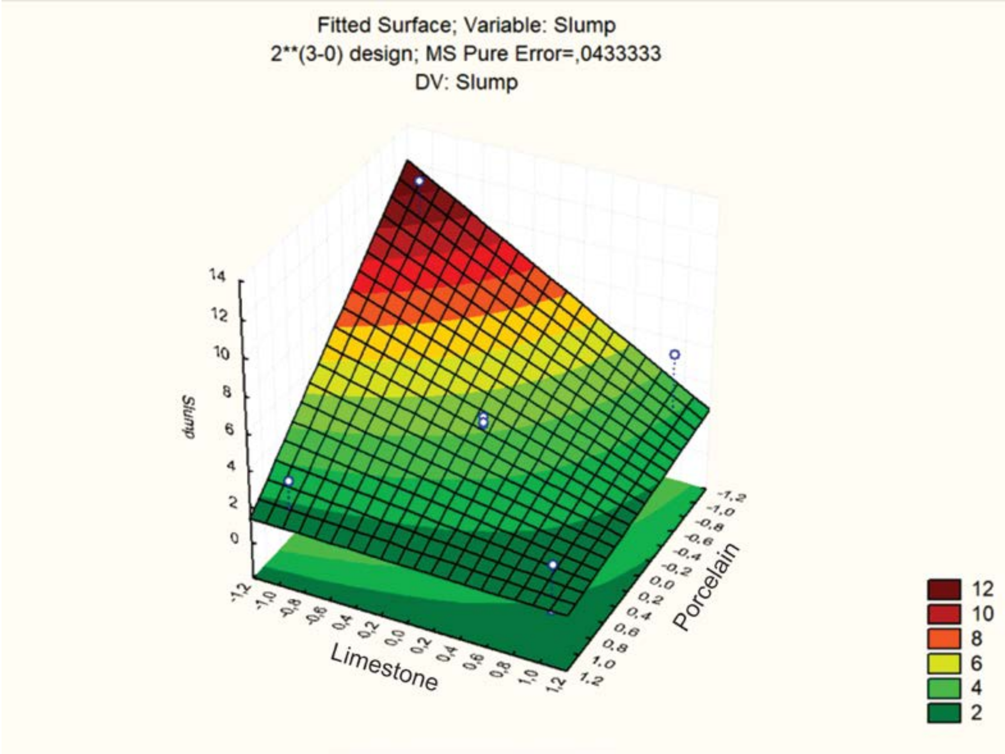

Figure 11 Fiited surface of Slump with TRR fixed in +1

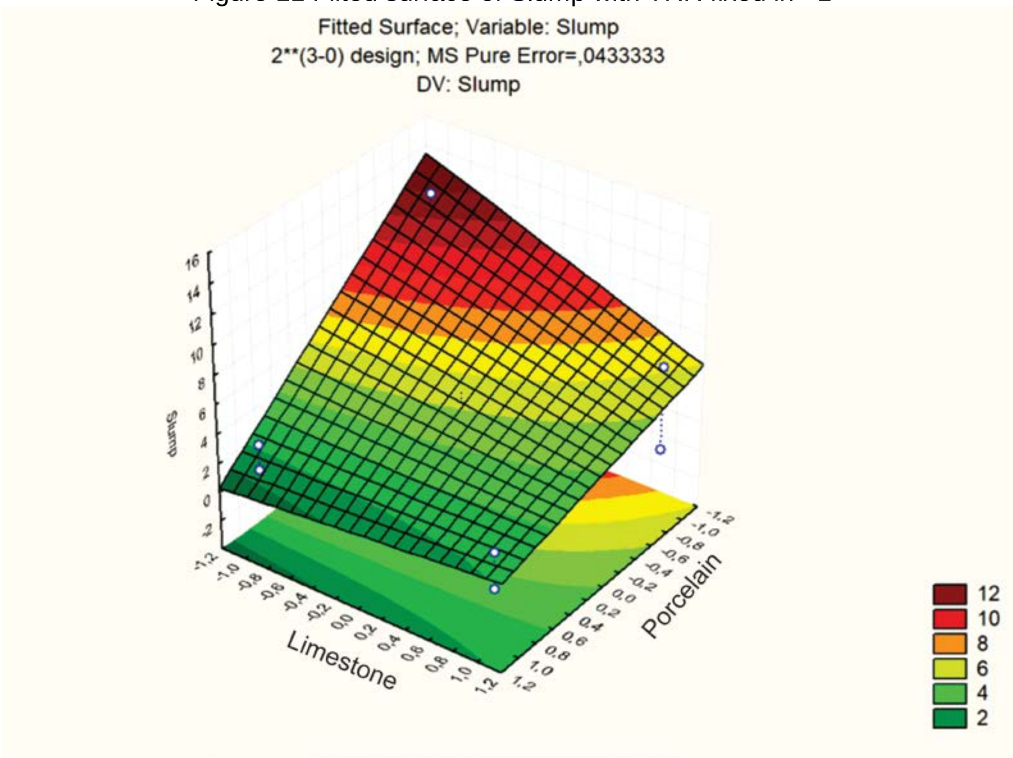

Figure 12 Fiited surface of Slump with PPR fixed in -1

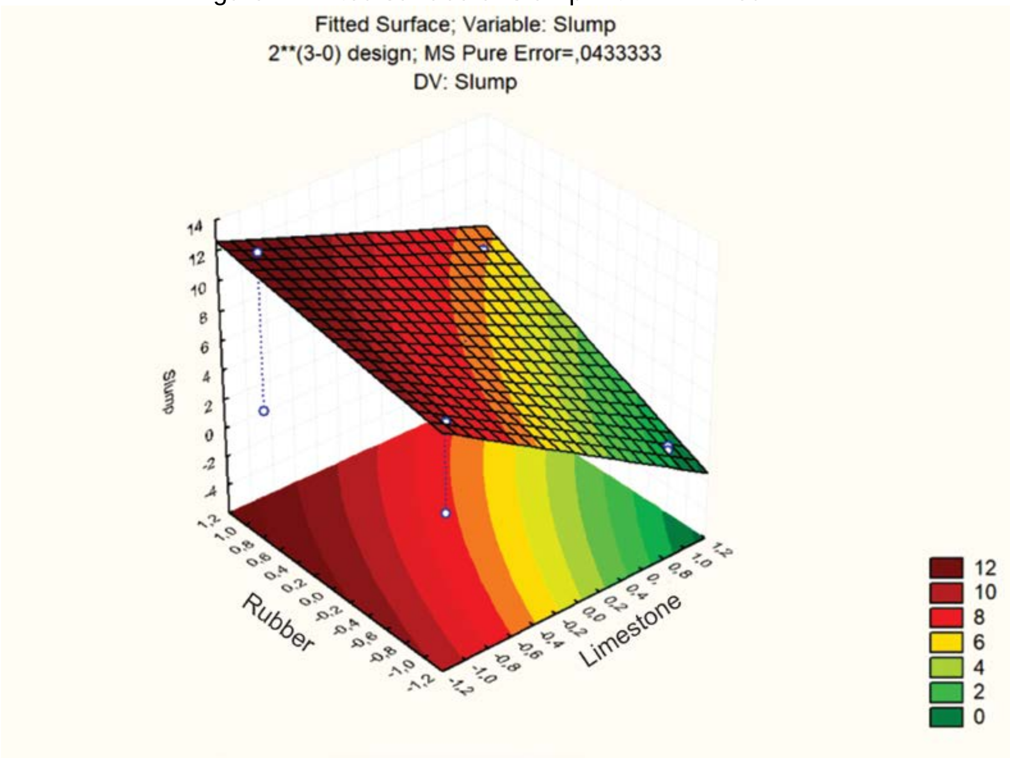

Figure 13 Fiited surface of Slump with PPR fixed in 0

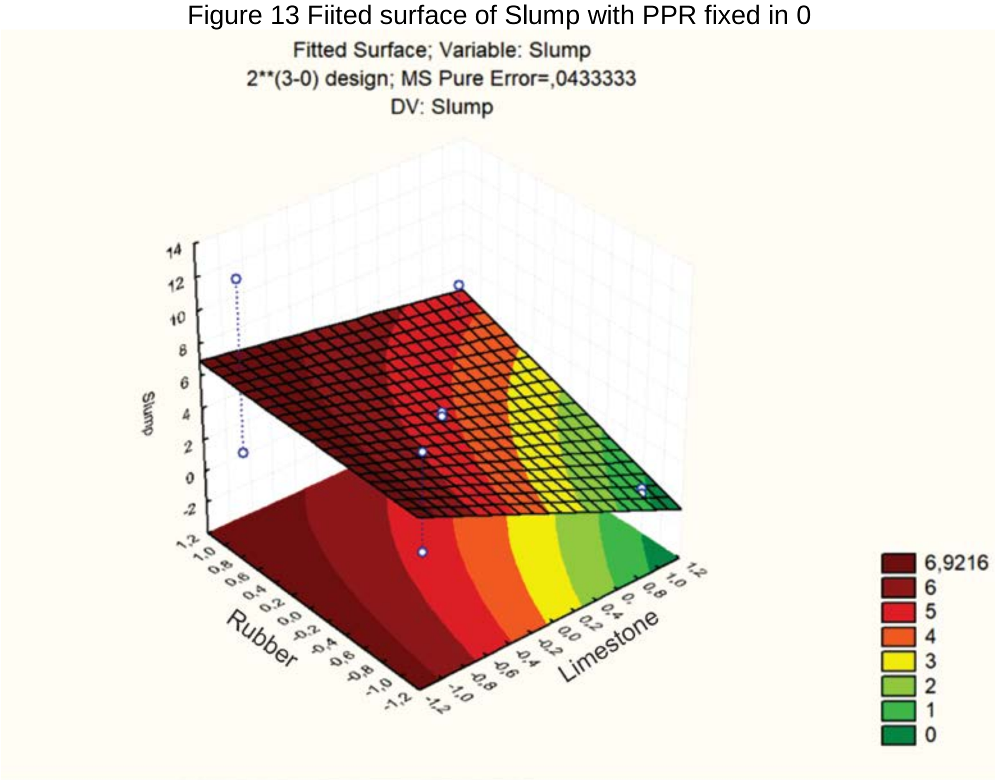

Figure 14 Fiited surface of Slump with PPR fixed in +1

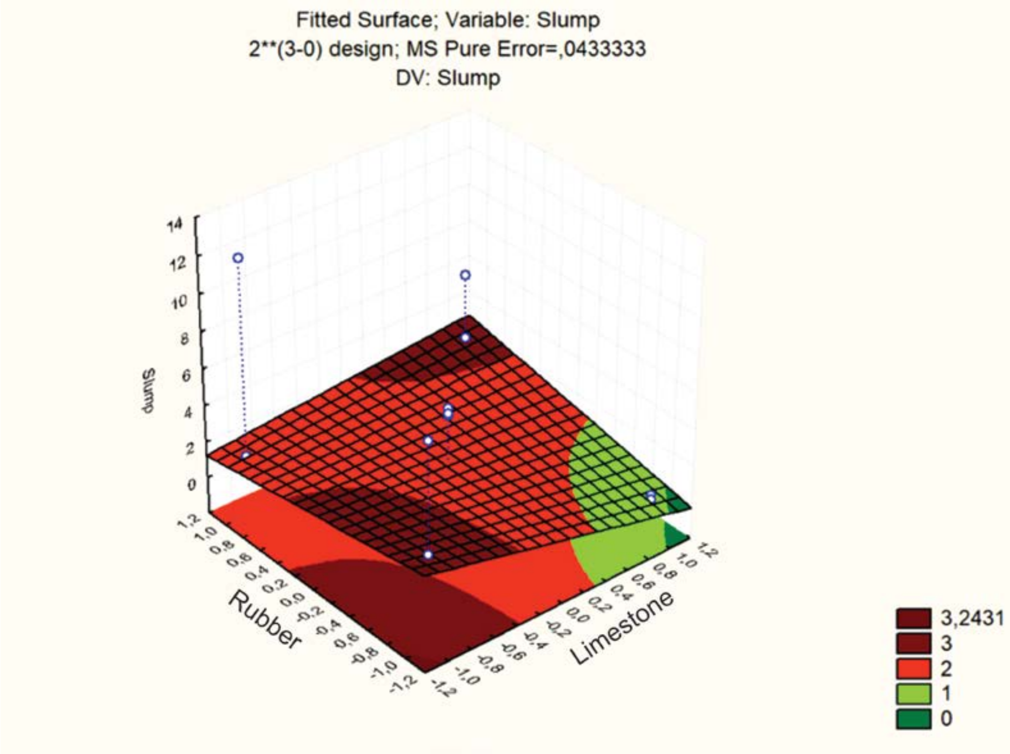

Figure 15 Observed versus predicted values of Slump

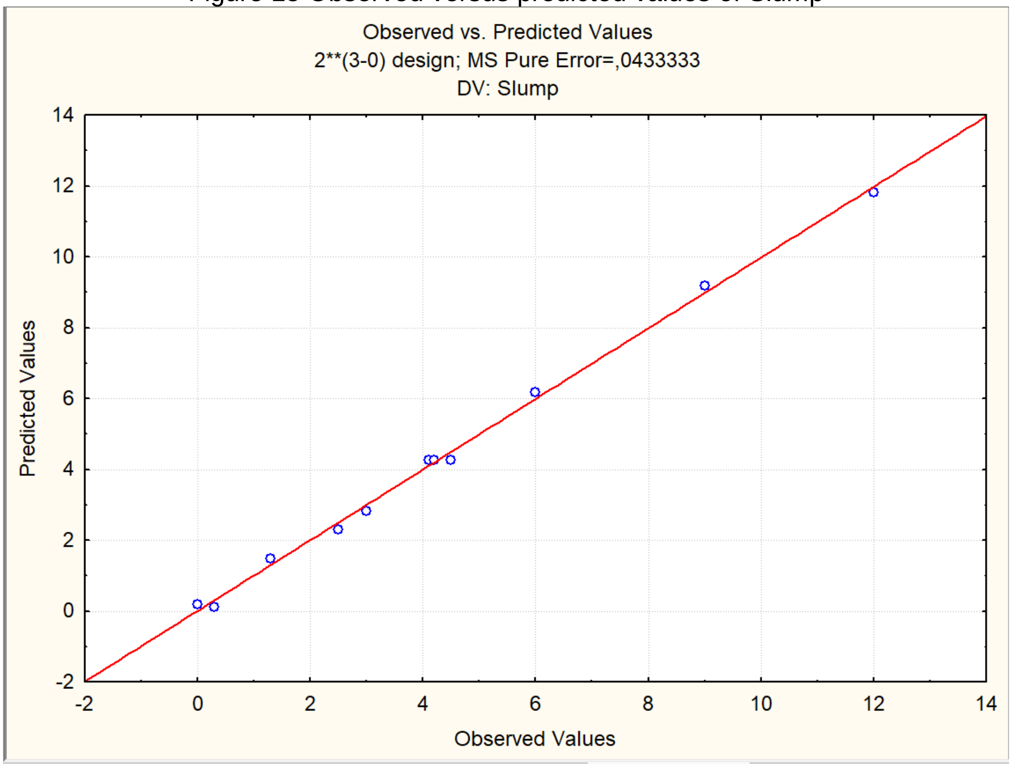

Table 11 Effect estimates of density

Factor	Effect Estimates; Var.:Density ; R-sqr=,8381; Adj:,46035 (zodinio statistica Massa Eesp in Work 2**(3-0) design; MS Pure Error=572,1483 DV: Density Effect	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	1637,519	7,21204	227,0536	0,000019	1606,488	1668,550	1637,519	7,212037	1606,488	1668,550
(1)Porcelain	20,357	16,91373	1,2036	0,351874	-52,416	93,131	10,179	8,456863	-26,208	46,566
(2)Limestone	-32,558	16,91373	-1,9249	0,194116	-105,331	40,216	-16,279	8,456863	-52,666	20,108
(3)Rubber	45,262	16,91373	2,6761	0,115866	-27,511	118,036	22,631	8,456863	-13,756	59,018
1 by 2	-3,923	16,91373	-0,2319	0,838175	-76,696	68,851	-1,961	8,456863	-38,348	34,426
1 by 3	-9,633	16,91373	-0,5695	0,626449	-82,406	63,141	-4,816	8,456863	-41,203	31,571
2 by 3	6,192	16,91373	0,3661	0,749375	-66,581	78,966	3,096	8,456863	-33,291	39,483
1*2*3	-22,083	16,91373	-1,3056	0,321673	-94,856	50,691	-11,041	8,456863	-47,428	25,346

Table 12 Regression coefficients of density

Factor	Regr. Coefficients; Var.Density ; R-sqr=,8381; Adj:,46 2**(3-0) design; MS Pure Error=572,1483 DV: Density Regressn Coeff.	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	1637,519	7,212037	227,0536	0,000019	1606,488	1668,550
(1)Porcelain	10,179	8,456863	1,2036	0,351874	-26,208	46,566
(2)Limestone	-16,279	8,456863	-1,9249	0,194116	-52,666	20,108
(3)Rubber	22,631	8,456863	2,6761	0,115866	-13,756	59,018
1 by 2	-1,961	8,456863	-0,2319	0,838175	-38,348	34,426
1 by 3	-4,816	8,456863	-0,5695	0,626449	-41,203	31,571
2 by 3	3,096	8,456863	0,3661	0,749375	-33,291	39,483
1*2*3	-11,041	8,456863	-1,3056	0,321673	-47,428	25,346

Table 13 ANOVA of density

Factor	ANOVA; Var.:DV_ 1; R-sqr=,8381; Adj:,46035 2**(3-0) design; MS Pure Error=572,1483 DV: DV_ 1 SS	df	MS	F	p
(1)Porcelain	828,856	1	828,856	1,448673	0,351874
(2)Limestone	2119,982	1	2119,982	3,705301	0,194116
(3)Rubber	4097,388	1	4097,388	7,161409	0,115866
1 by 2	30,772	1	30,772	0,053783	0,838175
1 by 3	185,570	1	185,570	0,324339	0,626449
2 by 3	76,694	1	76,694	0,134046	0,749375
1*2*3	975,274	1	975,274	1,704582	0,321673
Lack of Fit	461,817	1	461,817	0,807163	0,463775
Pure Error	1144,297	2	572,148		
Total SS	9920,648	10			

Figure 16 Observed versus predicted values of density

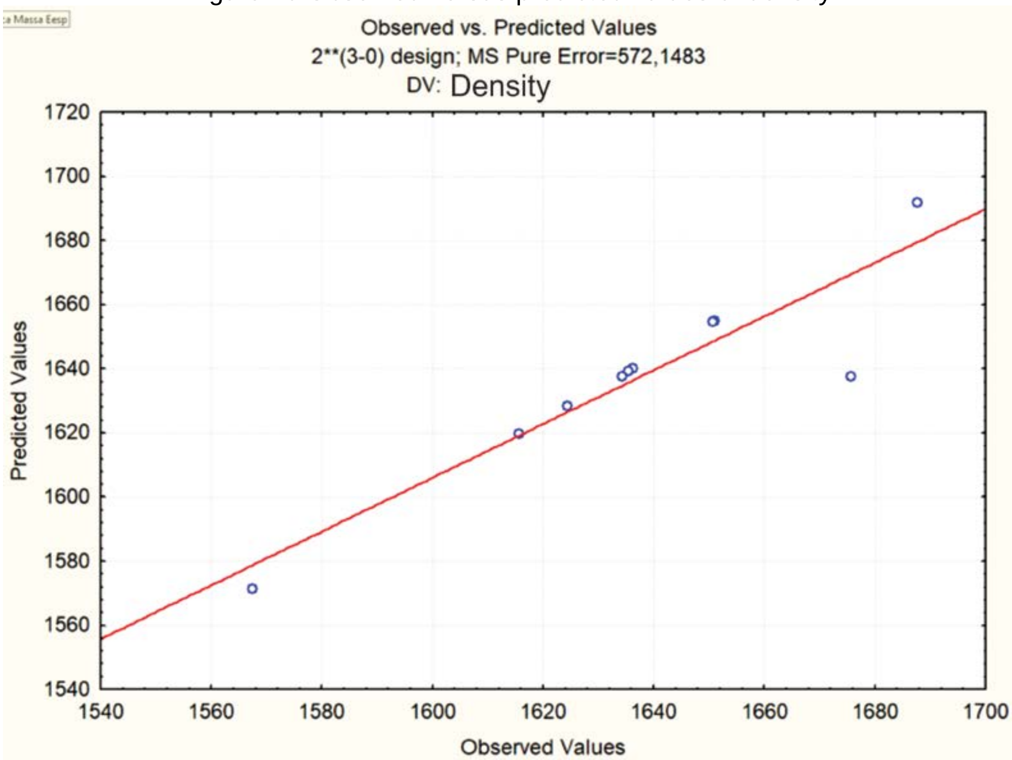

Table 14 Effect estimates of absorption

Effect Estimates; Var.:Absorption R-sqr=,70948; Adj:,03161 (Voids in Workbook voids)
2**(3-0) design; MS Pure Error=,0354333
DV: Absorption

Factor	Effect	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	7,355455	0,056756	129,5985	0,000060	7,11125	7,599655	7,355455	0,056756	7,111254	7,599655
(1)Porcelain	-0,455000	0,133104	-3,4184	0,075956	-1,02770	0,117700	-0,227500	0,066552	-0,513850	0,058850
(2)Limestone	-0,620000	0,133104	-4,6580	0,043129	-1,19270	-0,047300	-0,310000	0,066552	-0,596350	-0,023650
(3)Rubber	1,520000	0,133104	11,4196	0,007581	0,94730	2,092700	0,760000	0,066552	0,473650	1,046350
1 by 2	0,510000	0,133104	3,8316	0,061862	-0,06270	1,082700	0,255000	0,066552	-0,031350	0,541350
1 by 3	-0,550000	0,133104	-4,1321	0,053878	-1,12270	0,022700	-0,275000	0,066552	-0,561350	0,011350
2 by 3	0,735000	0,133104	5,5220	0,031265	0,16230	1,307700	0,367500	0,066552	0,081150	0,653850
1*2*3	-0,805000	0,133104	-6,0479	0,026267	-1,37770	-0,232300	-0,402500	0,066552	-0,688850	-0,116150

Table 15 Regression coefficients of absorption

Regr. Coefficients; Var.:Absorption; R-sqr=,59212; Adj:,32021 (Ã-nd
2**(3-0) design; MS Pure Error=,0354333
DV: Absorption

Factor	Regressn Coeff.	Std.Err. Pure Err	t(2)	p	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	7,355455	0,056756	129,5985	0,000060	7,111254	7,599655
(2)Limestone	-0,310000	0,066552	-4,6580	0,043129	-0,596350	-0,023650
(3)Rubber	0,760000	0,066552	11,4196	0,007581	0,473650	1,046350
2 by 3	0,367500	0,066552	5,5220	0,031265	0,081150	0,653850
1*2*3	-0,402500	0,066552	-6,0479	0,026267	-0,688850	-0,116150

Table 16 ANOVA of absorption

Factor	ANOVA; Var.:Absorption; R-sqr=,59212; Adj:,3 2**(3-0) design; MS Pure Error=,0354333 DV: Absorption				
	SS	df	MS	F	p
(2) Limestone	0,76880	1	0,768800	21,6971	0,043129
(3) Rubber	4,62080	1	4,620800	130,4083	0,007581
2 by 3	1,08045	1	1,080450	30,4925	0,031265
1*2*3	1,29605	1	1,296050	36,5771	0,026267
Lack of Fit	5,27871	4	1,319677	37,2439	0,026319
Pure Error	0,07087	2	0,035433		
Total SS	13,11567	10			

Figure 17 Observed versus predicted values of density