



Mechanical and Thermal Properties of Geopolymerized LECA Concrete

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Abstract

This study aims to enhance the mechanical and thermal performance of lightweight expanded clay aggregate (LECA) concrete through geopolymerization using iron oxide (Fe_2O_3) and polyethylene glycol 400 (PEG400), combined with surface treatment of LECA aggregates. An experimental program was conducted to evaluate workability, density, water absorption, compressive strength, splitting tensile strength, and bulk electrical resistivity (BER). Various mixtures with different proportions of Fe_2O_3 and PEG400 were prepared with and without aggregate surface treatment. The findings indicate that surface treatment significantly improves the interfacial transition zone, resulting in enhanced overall performance. The optimal mix (treated LECA with 3% PEG400 and 20% Fe_2O_3) achieved a compressive strength of 45 MPa and a splitting tensile strength of 4.0 MPa, representing increases of over 70% compared to the control mix. Additionally, water absorption decreased by 35.6%, while BER increased by 127%, reflecting improved durability and reduced permeability. Workability was also enhanced, with up to a 100% increase in slump without compromising strength. The novelty of this study lies in the synergistic integration of treated LECA, PEG400, and iron oxide within a geopolymer matrix to produce a high-performance, durable, and thermally efficient lightweight concrete. This approach offers a sustainable solution for advanced construction applications.

Keywords: LECA; Geopolymer; Iron Oxide; Bulk Electrical Resistivity; Thermal; Lightweight.

1. Introduction

Concrete components make up the majority of the structure's dead load and are its heaviest weight [1]. In addition to having a better fire resistance than regular weight aggregate concrete, lightweight concrete is employed to reduce the overall dead load in constructions [1, 2]. Concrete that contains both natural and synthetic lightweight aggregate, such as lightweight expanded clay aggregate (LECA), is referred to as lightweight concrete [1, 3]. Made in a rotary kiln, LECA is a unique method of lowering the self-weight of concrete that is around 50% lighter than ordinary aggregate [1, 4]. The two main types of lightweight aggregates utilized in LWC are organic and inorganic (natural and manmade), Light-weight expanded clay aggregate (LECA) is one of the inorganic synthetic materials that has become more and more popular in recent years [5, 6]. LECA is a porous aggregate made by heating clay to 1150 degrees Celsius in rotary

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furnaces [5, 7]. This causes the product to expand by four to five times its initial dimensions, producing roughly spherical particles with a rough surface [5]. Because of its low specific weight, low conduction coefficient, and typically excellent chemical stability, LECAS is currently often used to create LWC in various regions of the world [2, 5, 8]. LWC's higher resilience to high heat and fire is a significant advantage over NSC [3, 9, 10].

The mechanical and load-carrying characteristics of concrete members may drastically change during a fire because concrete is a mixture of constituents with different thermal properties as well as attributes that are reliant on moisture and porosity [9, 10]. The presence of pores in the lightweight aggregates, which may offer a way to relieve the increased steam pressure, is the primary reason why LWC has a stronger fire resistance than NSC [10-12]. Light Expanded Clay Aggregate (LECA), which is produced by heating clay to 1200°C in a rotating kiln, is one example of a lightweight aggregate. LECA is a spherical organism with an uninterrupted pore network [7, 13, 14]. Lightweight blocks, concrete, separation panels, thermal insulation tiles, fireproof roof gypsum, and concrete batches can all be made with LECA [8, 15]. The novel material known as lightweight geopolymer concrete (LWGPC) combines the benefits of both lightweight concrete and geopolymer concrete [16]. By using zero percent cement concrete ingredients and increasing the use of geopolymer concrete (GPC), this concrete provides a great solution to lower a structure's self-weight [17]. Kumar et al. [9] stated that thermal insulation, lower energy costs, increased building efficiency, and ease of construction are all benefits of lightweight aggregate concrete (LWAC). Additionally, there are advantages for environmental sustainability when industrial wastes are used in concrete. To study this, a number of scholars looked into the idea of using industrial wastes in LWAC. However, the lack of knowledge about the performance of lightweight aggregate concrete based on industrial waste hinders the implementation of this concept and the usage of LWAC in the construction industry. Also, Murugan et al. [11] discovered that basalt-pumice aggregate, 450 kg/m³ cement, and 10% silica fume can be used to create lightweight concrete with a 90-day compressive strength of 43.8 MPa and a dry density of 1,860 kg/m³ [9, 14, 18]. On the other hand, using Brazilian LWC might result in lightweight concrete with a dry density of 1,605 kg/m³ and a 28-day compressive strength of 53.6 MPa [18].

It was discovered that in Portland cement-based concrete, iron oxides produced by the corrosion of a steel reinforcing bar accumulated at the interfaces between aggregate and cement paste [19-21]. Severe deterioration of housing foundations in different countries around world has lately been connected to oxidation of aggregates containing iron sulfide minerals [22, 23]. Most performance-based techniques currently in use rely on the use of oxidizing solutions, which might result in harsh circumstances and unexpected effects [22, 24]. Amjad et al. [23] and Krishnan et al. [25] discovered a way to improve the mechanical and durability characteristics of EPW aggregate concrete by adding sisal fiber (SsF) reinforcement and nano iron oxide particles (NIOP). 30% EPW coarse aggregate (EPWCA) was used in place of some natural coarse aggregates [23]. By adding 1% SsF and adjusting the NIOP content from 1.0% to 4% of the cement's weight, the performance of the final concrete was carefully examined [23]. Both NIOP and SsF intrusion reduce the workability of concrete [23]. Nevertheless, the hardened density of the final concrete is reduced and increased, respectively, by the inclusion of SsF and NIOP [23]. The performance of EPW concrete was improved by the combination of NIOP and SsF reinforcement; the EPW concrete modified with 4% NIOP and 1% SF demonstrated the best performance [23, 26, 27]. The elastic characteristics of iron oxides produced in reinforced concrete buildings are discovered by Ouglova et al. [28]. Since it is difficult to perform mechanical tests on the actual oxides, which are shown as (many) laminated stratum, the elastic modulus of iron oxides is yet unknown. [20, 28]. Acoustic measurements and oedometric tests were used to determine the Young's moduli of porous compact "synthetic oxides" in powder form that were generated under laboratory settings [26, 28].

Because of its exceptional hydrogel properties and ease of development, bacterial cellulose (BC) is currently one of the natural materials at the forefront of innovation in engineered living materials (ELMs) research [29, 30]. However, this material's rapid drying in open spaces as water molecules escape the porous network is one of its primary drawbacks [29]. The alternative solvents with higher evaporation temperatures, such as glycerol and polyethylene glycol (PEG), can interact with cellulose fibers through hydrogen bonds in the BC structure in a manner similar to that of water [29, 31, 32]. The molecules, in a concentration-dependent way, increase the Young's modulus of BC hydrogels to compression stresses by up to 130 times [33, 34]. Longkumer & Gupta [34] examined how the strength of concrete can be determined by substituting admixtures such as Polyethylene Glycol-400 (PEG400) and Rice Husk Ash (RHA) for some of the cement. RHA is an additive used in concrete construction because of its high silica concentration (approximately 90%), which indicates pozzolanic activity and cementitious properties [34, 35]. As a result, we can partially replace it and examine its impact on the concrete's strength. They use the PEG-400 chemical, a shrinkage-reducing additive, as a curing material [34]. A self-curing chemical called PEG-400 adds more moisture to the concrete to improve its hydration [34]. It prevents water from evaporating from the concrete by reducing its shrinkage [34, 36, 37]. Al-Jabali et al. [17] explained how the continuous replacement of 50% of the coarse aggregate with zeolite as a filler and PEG-400 as a plasticizer, water retention agent, and strength booster affects the mechanical properties of LECA and foamed concrete, two types of lightweight concrete. A study examining the characteristics of cellular lightweight concrete in both its fresh and hardened forms was carried out for both foamed and LECA-concrete.

This was accomplished by using the direct absorption approach to create a composite of zeolite and polyethylene glycol 400, and no leakage was observed [38-40]. A lot of research studies on water saving in concrete are desperately needed as water supplies grow more limited [32, 41, 42]. Consequently, attempts have been undertaken to create self-curing concrete using polyethylene glycol 400 (PEG-400) as a self-curing component [41-43]. When it is not financially possible to use purified water, work is often done in places with acute water shortages [41]. PEG-400, a self-curing agent, is used in the current study at weight percentages of 0%, 0.5%, 1%, and 2% [37, 39, 41]. Most self-curing concrete mixes became denser when PEG-400 was added [36, 37, 41]. Better internal curing and less evaporation are the main causes of higher early-age density [31, 32]. However, high PEG-400 reduced density, indicating that 0.5% PEG-400 is a suitable dosage level [36, 44].

1.1. Research Significance

This study contributes to the growing body of knowledge on sustainable construction materials by integrating geopolymer technology with lightweight concrete systems. Its significance can be outlined across several critical dimensions, Sustainability and Waste Valorization: Geopolymer binders, derived from industrial by-products such as fly ash or slag, offer a low-carbon alternative to Portland cement. Their use reduces greenhouse gas emissions and promotes circular economy practices. Iron oxide, incorporated into recycled aggregates, not only enhances mechanical performance but also vaporizes industrial residues that would otherwise pose disposal challenges. PEG-400 serves as a stabilizing agent, improving the microstructure and durability of recycled aggregates, ensuring their compatibility with geopolymer matrices. Advancement in Lightweight Concrete Technology: Lightweight Expanded Clay Aggregate (LECA) is widely recognized for reducing structural dead loads and improving thermal insulation. By combining LECA with iron oxide/PEG400-based geopolymer recycled aggregates, this research advances lightweight concrete technology toward higher efficiency and broader applicability. Mechanical properties such as compressive strength, flexural strength, and durability are systematically evaluated to ensure the material meets engineering and structural standards. Thermal Performance and Energy Efficiency: Thermal conductivity and insulation capacity are crucial for modern buildings aiming to reduce energy consumption. This study investigates how geopolymer-modified recycled aggregates influence the thermal behavior of LECA concrete, contributing to energy-efficient building envelopes. Enhanced thermal performance directly supports global efforts to design sustainable, low-carbon structures. Contribution to Circular Economy and Green Construction: By integrating recycled aggregates, iron oxide, and geopolymer binders, the research aligns with circular economy principles, reducing reliance on virgin raw materials and lowering the environmental footprint of construction. The findings provide a pathway for integrating eco-friendly aggregates into mainstream concrete production, encouraging industry adoption and supporting sustainable infrastructure development.

Main Purpose of the Research The primary aim of this study is to evaluate the mechanical strength and thermal efficiency of LECA lightweight concrete when partially substituted with iron oxide/PEG400-based geopolymer recycled aggregates, thereby determining its feasibility as a sustainable construction material. The outcomes are expected to establish a balance between structural integrity, thermal performance, and environmental sustainability, offering practical solutions for modern infrastructure projects. As shown, Figure 1 also presented the display work methodology.

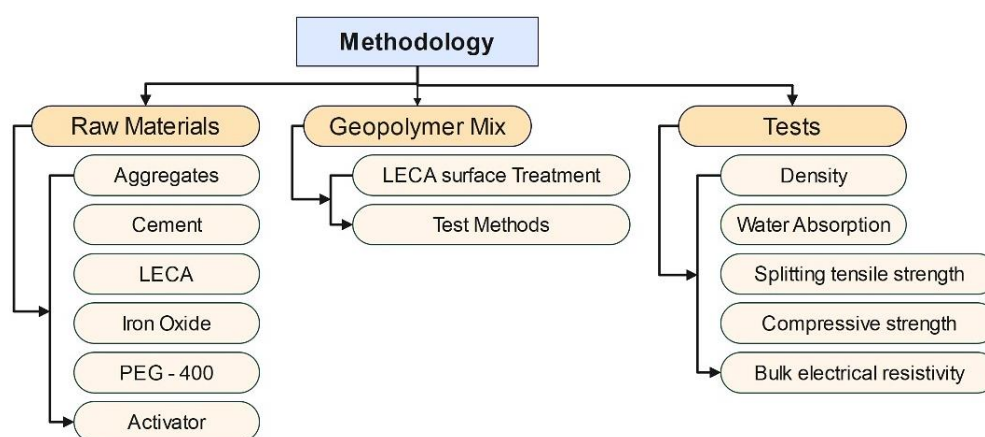


Figure 1. Presented Work Methodology – By authors

2. Materials and Methods

This section provides a prologue to the materials employed and their compliance with ASTM specifications, as well as an overview of the trial program lead for this assessment. The analysis looks into the use of entirely replacing nature coarse aggregate by treated LECA by alkaline Iron Oxide/PEG-400. The goal is to develop a new thermal resist LWC that is strong enough and safe for the environment, thereby improving the eco-friendliness and maintainability of the concrete industry.

2.1. Aggregates

The substantial employed regular sand as fine aggregate (FA) with a specific gravity of 2.59 and natural coarse limestone aggregate (NCA), which was used as coarse aggregate with an NMS of 19 mm. For every significant blend in the underlying set, the fine total, which ranged in size from 0.15 to 1.2 mm, was used. Both FA and NCA comply with the ASTM C33/C33M-08 standard determination [45]. Table 1 lists their individual mechanical and physical characteristics.

Table 1. Mechanical and physical characteristics of (NCA), (FA) and LECA

Properties	Aggregate		
	Natural limestone Coarse aggregates (NCA)	Sand - Fine aggregates (FA)	LECA
Crushing value %	17.33	-	27
Los Angeles abrasion %	17.45	-	36
Specific gravity	2.67	2.56	2.22
Volume density Kg/m ³	1427	1559	569
Water absorption%	0.75	1.88	22

2.2. Ordinary Portland Cement (OPC)

Ordinary Portland cement is one of the most widely used types. In this study, Portland concrete [CEM-42.5 N], which has a specific gravity of 3.17 g/cm³ and a specific surface area of 3070 cm²/gm, was used in the study. Additionally, the compliance of the [CEM-42.5 N] grade regular Portland cement used with ECP203 is investigated [46]. Table 2 below lists the specifications of the cement used in the study.

Table 2. OPC Properties

Property	Typical Value / Description
Compressive strength - MPa	≥ 20 MPa at 2 days; ≥ 42.5 MPa at 28 days
Setting Time – min.	37 min. (Initial setting ≥ 60 minutes)
Finess - %	4.76 %
Specific gravity	2.89
Consistency	37 %
Standards Compliance	[46, 47]

2.3. Lightweight Expanded Clay Aggregate [LECA]

As discovered before by Al-Jabali et al. [17], the LECA aggregate was weighed dry and then immersed in water for a few days. Before mixing, the aggregate was put on a sieve for about half an hour to remove any extra water. On the other hand, the LECA aggregate, which has a specific gravity of 2.22 and a density of 569 kg/m³, was used without any prior soaking. The ECP Committee [46] is followed for conducting the coarse aggregate (LECA) tests. The LECA used in this study was purchased from the BGN firm in Egypt. Additionally, Table 1 shows LECA's physical attributes. An illustration of the LECA is shown in Figure 2. For better understanding, Figure 3 presents the particle size distribution of LECA and contrasts it with natural coarse aggregate NCA.



Figure 2. Used LECA (BGN company-Egypt) [17]

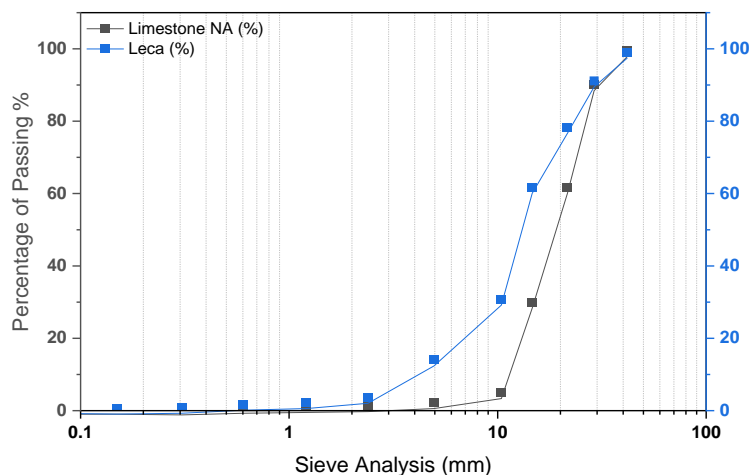


Figure 3. Particle size distribution for (Limestone - NA) and (LECA)

2.4. Iron Oxide – Fe₂O₃

Iron oxide (Fe₂O₃) is a widely used mineral additive in cementitious composites, and its properties directly influence both mechanical and thermal performance. In scientific terms, fineness is a critical parameter: iron oxide powders are typically ground to a fine particle size (often below 90 μm by sieve analysis or measured by Blaine fineness), which ensures uniform dispersion and effective participation in hydration reactions.

The oxide chemical analysis reveals that Fe₂O₃ is the dominant constituent, often exceeding 95% purity in industrial-grade materials, with minor traces of SiO₂, Al₂O₃, and TiO₂ depending on the source. Its specific gravity generally ranges between 5.0–5.2, significantly higher than Portland cement (≈3.15), which influences mix design and density considerations. While iron oxide itself is not a binder, when blended with cement it can affect setting times: the initial setting time of cementitious mixes remains above 60 minutes, and the final setting time typically does not exceed 600 minutes, in compliance with EN 197-1 standards [47]. These parameters ensure that iron oxide-modified concretes maintain workable consistency while benefiting from enhanced strength and durability. As illustrated in Table 3, it provides a detailed overview of the chemical composition of used iron oxide.

Table 3. Iron Oxide [Fe₂O₃] & OPC Chemical composition

Material	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O
Iron Oxide – Fe ₂ O ₃	1.7	0.38	1.25	97.85	0.17	0.21	0.13
OPC	21	61.88	6.35	3.18	3.28	0.04	-

Local chemical suppliers, distributors of building materials, and marketplaces for industrial raw materials can easily obtain iron oxide powders. Iron oxide in several grades (pigment-grade, cement additive-grade, and industrial-grade) packaged in 25–50 kilogram sacks is supplied by major suppliers in Cairo and Alexandria. Iron oxide used in this study was obtained from "Al Fanar Al Jadidah Mining Company – Cairo – Egypt," which produces it with molecular size #200. According to ASTM C 150 [48]. This accessibility makes iron oxide a practical and cost-effective additive for research and construction applications in the region. Figure 4 depicts iron oxide as raw material. Figure 5 produces the particle size distribution of OPC compared with iron oxide [Fe₂O₃].



Figure 4. Iron Oxide – Fe₂O₃ as raw material

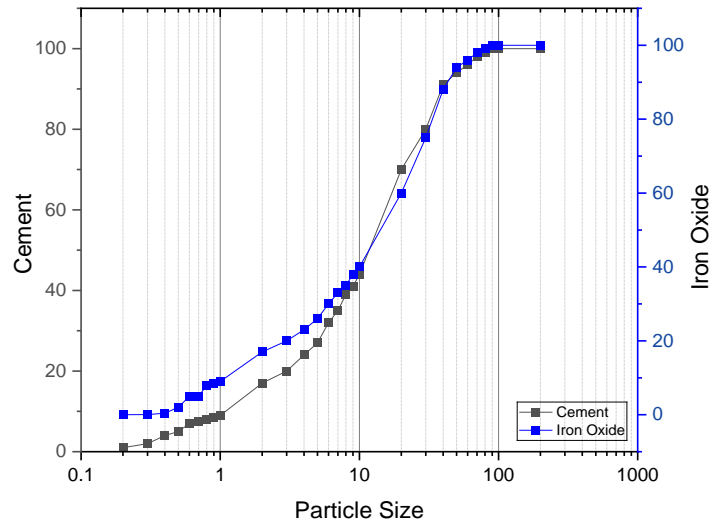


Figure 5. OPC and Iron oxide Fe₂O₃ Particle size distribution

2.5. Polyethylene Glycol [PEG-400]

PEG-400, one of the most popular water-soluble polymers, dissolves in a range of organic solvents, including aromatic hydrocarbons. Among other precise distribution features, PEG-400 is used as a plasticizer to speed up lubricity and workability in concrete mixtures, adhesives, binders, and soldering fluxes. It also serves as a water retention agent. A number suffix of groups with particular average molecular weights is what distinguishes polyethylene glycol. The molecular weight of PEG ranges from 300 g/mol to 1 × 10⁷ g/mol. As discovered previously by Al-Jabali et al. [17], this work uses PEG-400, which has a molecular weight of 400 g/mol and was purchased from Desert Chart Company in Egypt. Table 4 displays the characteristics of PEG-400. Figure 6 displays a picture of PEG-400.

Table 4. Characteristics of PEG-400

Properties	Value
Appearance	Solution (Water soluble)
OPC	21
Specific gravity	1.12
Molecular weight	400 (g/mol)
Density	1.12 (gm/cm ³)



Figure 6. Solution of PEG-400

2.6. Mixing Water and Alkaline Activator Solution

The drinking water complies with ASTM C1602/C1602M-18 guidelines [49]. The dry ingredients were blended, and the considerable amount was relieved using consumable water. For every blend, the water-to-solidify proportion (W/C) remained constant at 0.35.

Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used as alkaline activators. Na at 16.17%, O at 67.55%, H at 6.38%, and Si at 9.88% by mass made up the sodium meta-silicate ($\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$) solution. It had a melting point of 1.088 °C and a density of 2.4 g/cm³. High specific gravity glass water, or sodium meta-silicate, is a colorless crystal with a molecular weight (M.W.) of 284.2 g/mole and a purity of 98%. NaOH had a molecular weight (M.W.) of 40 g/mol, a density of 2.13 g/cm³, a purity of 96%, and a melting temperature of 318 °C.

Na_2SiO_3 (water glass) and NaOH solution were used as an alkaline activator. One concentration was used. NaOH concentrations of 8 molarity (M) were investigated. The ratio of Na_2SiO_3 to NaOH was kept at 1. Before being combined with sodium meta-silicate, separate solutions of sodium hydroxide were made and let to stand for a full day.

The solutions comprising sodium hydroxide and sodium meta-silicate were let to stand for a day prior to being utilized in the geo-polymerization procedure. It takes a long time and a high temperature to prepare sodium silicate alkaline in liquid form from sodium meta-silicate ($\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$) in particle form. It is therefore more convenient to obtain and use it initially in liquid form. For example, Morgan Specialty Chemicals Company in Al Obour, Egypt, sells sodium silicate alkaline in a 50±0.2 kg box.

3. Geo-Polymer Concrete Mix Design

3.1. LECA Surface Treatment

As indicated in Table 5, the OPC and Iron Oxide were combined with water to create the treatment solution. The solution had 8 M NaOH and a 10% concentration (binder to water ratio).

Table 5. LECA treatment solution for a 1000 g

LECA surface treatment solution	Binder (g)		LECA (g)	Water (g)	(Binder to water ratio)	NaOH (M)
	PC	Iron Oxide				
PC + Iron Oxide	80	60	1000	2000	10 %	8

After cleaning, LECA were immersed in the prepared solution for four hours [50]. After being taken out of the solution, the treated LECA were allowed to drain for ten minutes in a bath before being allowed to air dry for a full day at room temperature.

3.2. Treated/Untreated LECA Concrete Proportion

The experimental program aimed to ascertain the strength of lightweight concrete by incorporating polyethylene glycol (PEG400) into the concrete at weight percentages of 1%, 2%, and 3%. The targeted values for the dry density, sand-binder ratio, and water-binder ratio were 0.45, 1:1.5, and 1250 kg/m³, respectively. ACI C-211 guidelines [51] were followed in the formulation of the mixture. For the OPC concrete control mixes, a target strength of 35 MPa were established. Table 6 provides the combination proportions for different mix. Also, this study describes the continuous replacement of 100% of the treated LECA.

Table 6. The combination proportions for different mix

Mix Id	Mix. Designation	Target density (kg/m ³)	Binder		Sand (kg/m ³)	Water (kg/m ³)	8 M		Na_2SiO_3 Solution (kg/m ³)	LECA (kg/m ³)	PEG-400 (kg/m ³)	Agg. Status
			Cement (kg/m ³)	Iron Oxide (kg/m ³)			NaOH Solution (kg/m ³)					
C	CM/L	1250	465	--	698	210	40	80	23	--	U	
1/U/10	UL-1P/10I/M8	1250	465	46.5	698	205.35	40	80	23	5.11	U	
1/T/10	TL-1P/10I/M8	1250	465	46.5	698	205.35	40	80	23	5.11	T	
2/U/10	UL-2P/10I/M8	1250	465	46.5	698	203	40	80	23	7.67	U	
2/T/10	TL-2P/10I/M8	1250	465	46.5	698	203	40	80	23	7.67	T	
3/U/10	UL-3P/10I/M8	1250	465	46.5	698	200.7	40	80	23	10.23	U	
3/T/10	TL-3P/10I/M8	1250	465	46.5	698	200.7	40	80	23	10.23	T	
1/U/20	UL-1P/20I/M8	1250	465	93	698	205.35	40	80	23	5.11	U	
1/T/20	TL-1P/20I/M8	1250	465	93	698	205.35	40	80	23	5.11	T	
2/U/20	UL-2P/20I/M8	1250	465	93	698	203	40	80	23	7.67	U	
2/T/20	TL-2P/20I/M8	1250	465	93	698	203	40	80	23	7.67	T	
3/U/20	UL-3P/20I/M8	1250	465	93	698	200.7	40	80	23	10.23	U	
3/T/20	TL-3P/20I/M8	1250	465	93	698	200.7	40	80	23	10.23	T	

UL-1P/10I/M8: "UL" means Untreated Leca while "T" means geo-polymerized treated LECA, "1P" means 1% of PEG400 as weight percentage of concrete, "10 I" means 10% of Iron oxide Fe_2O_3 as additive from cement % and "8M" means that molarity of NaOH equal 8 M

Also, Table 6 presents the complete mix design for 18 concrete mixtures, systematically organized to evaluate the individual and synergistic effects of LECA surface treatment, PEG400 dosage, and iron oxide content within a geopolymer matrix. The table is structured with each mix identified by a unique code (e.g., TL-3P/20I/M8), where “UL” denotes untreated LECA, “T” denotes treated LECA (via an alkaline solution of OPC and iron oxide), “1P/2P/3P” indicates the PEG400 content as a percentage of total concrete weight, “10I/20I” specifies iron oxide (Fe_2O_3) added as 10% or 20% of cement weight, and “M8” signifies an 8-molarity NaOH alkaline activator. All mixes target a constant density of 1250 kg/m^3 and a consistent sand–binder ratio. The binder system consists of OPC (465 kg/m^3) supplemented with iron oxide (46.5 kg for 10% or 93 kg for 20%), while the alkaline activator comprises NaOH solution ($205\text{--}210 \text{ kg}$) and sodium silicate (80 kg) in a 1:1 ratio to promote geopolymerization. Fine aggregate (sand) is held at approximately 698 kg/m^3 , and LECA coarse aggregate is fixed at 408 kg/m^3 regardless of treatment. PEG400 is added in increasing amounts (235 to 310 kg) corresponding to 1%, 2%, and 3% by concrete weight.

The control mix (CCM/L) contains no iron oxide, no PEG400, and uses untreated LECA with a lower activator content, serving as the baseline. This factorial arrangement (2 treatment states \times 3 PEG400 levels \times 2 iron oxide levels, plus control) enables systematic assessment of how surface treatment improves the interfacial transition zone, how PEG400 enhances workability and pore refinement, and how iron oxide contributes to micro-filling and densification, ultimately allowing identification of the optimal synergistic combination (TL-3P/20I/M8) that yields superior mechanical and durability performance. Figure 7 shows the LECA during drying process.



Figure 7. (a) LECA as raw material after at treatment phase, and (b) The drying process of LECA in air

3.3. Test Methods

The ASTM C143 [52] slump flow table test was used on fresh mixtures to assess the workability of different LECA mixes. After 28 days, the water absorption of LECA mixes measuring $75 \times 100 \text{ mm}$ was calculated using BS 1881-122 [53]. After being submerged in water for a whole day, the samples were dried in an oven. ASTM C642-13 was used to evaluate the density of both kinds of hardened concrete specimens ($100 \times 100 \times 100 \text{ mm}$) 28 days after curing [54]. The compressive strengths of the LECA at 28 days were measured using a compression test equipment. The test loading rate was established at 0.1 kN/s in accordance with BS EN 12390 [55]. For every blend, three 100 mm cube samples were examined. According to BS EN 12390 [55], the concrete's splitting strength tensile was assessed following 28 days of curing. Cylinders measuring $100 \times 200 \text{ mm}$ were manufactured for each concrete mixture.

For the thermal test, two metal electrodes were positioned at the base and top of the cylinder in order to measure the bulk electrical resistivity (BER) directly [56]. The bottom of the cylinder and the metal plates were separated by two damp sponges. An ETCR model 3200C soil resistivity meter was then used to apply alternating current (AC) and a known current and voltage to the system. Each specimen was evaluated twice to determine the electrical resistance (R), and the average value was utilized. Equation 1 was used to get the electrical resistivity (ρ) based on each specimen's dimensions:

$$R_e = \frac{V}{I} = \rho \frac{L}{A} \quad (1)$$

$$\rho = R_e \frac{A}{L} \quad (2)$$

where, R_e is equal to electrical resistivity [Ω], V is the voltage [volts] between the electrodes, I is the electric current's intensity [amperes] as it passes through the substance, ρ Electrical resistivity [$\Omega \text{ cm}$] - [m], L is the conductive material's length [m] minus [cm], and A is equal to area or cross-section [m^2] minus [cm^2].

4. Results and Discussion

Table 7 illustrates values of all tests performed on all types of mixtures previously shown in Table 6. The results shown are for mechanical properties of concrete in both fresh and hardened states. For fresh concrete (the slump test was evaluated in "Figure 8"), hardened concrete (density test, compressive strength test, splitting tensile strength test, and water absorption test were conducted).

Table 7. Test results for LECA Lightweight Concrete with Iron Oxide/PEG400 mixes

Mix Id	Mix. Designation	Target density (kg/m ³)	Actual density (kg/m ³)	Slump (mm)	Compressive Strength (28 days - MPa)	Water Absorption (%)	Splitting Tensile (28 days - MPa)
C	CM/L	1250	1257	45	26	13.5	2.3
1/U/10	UL-1P/10I/M8	1250	1245	60	32	12.8	2.9
1/T/10	TL-1P/10I/M8	1250	1260	75	36	10.5	3.3
2/U/10	UL-2P/10I/M8	1250	1248	80	34	12.5	3.0
2/T/10	TL-2P/10I/M8	1250	1258	90	39	10.0	3.5
3/U/10	UL-3P/10I/M8	1250	1250	65	37	11.8	3.3
3/T/10	TL-3P/10I/M8	1250	1265	75	43	9.5	3.9
1/U/20	UL-1P/20I/M8	1250	1255	55	34	11.5	3.0
1/T/20	TL-1P/20I/M8	1250	1264	65	39	9.8	3.4
2/U/20	UL-2P/20I/M8	1250	1258	70	36	11.2	3.2
2/T/20	TL-2P/20I/M8	1250	1275	80	41	9.3	3.6
3/U/20	UL-3P/20I/M8	1250	1255	60	38	10.5	3.3
3/T/20	TL-3P/20I/M8	1250	1280	70	45	8.7	4.0



Figure 8. Slump test apparatus

4.1. Slump Test as Workability Indicator

As shown in Figure 9, in this study, slump test results revealed a consistent enhancement in workability across all treated LECA-based geopolymer concrete mixes compared to their untreated counterparts. Every treated mix shows a higher slump than its untreated counterpart, with increases ranging from +12.5% to +25%. The increase in slump for treated LECA mixes is attributed to the surface treatment of LECA, which enhances the aggregate’s compatibility with the geopolymer matrix, reducing internal friction and improving flowability. Also, PEG400 as a plasticizer acts as a dispersing agent, reducing water demand and improving workability.

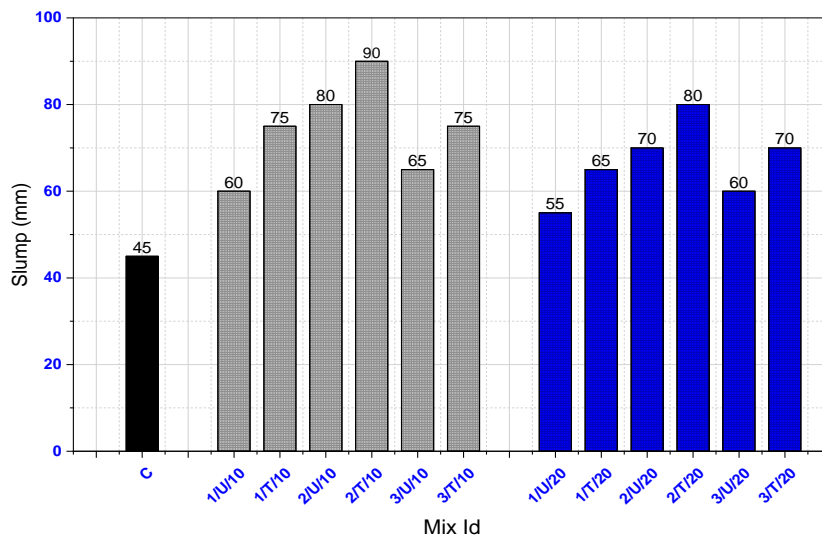


Figure 9. Slump of LECA Lightweight Concrete with Iron Oxide/PEG400 mixtures

Iron oxide influence may contribute to particle packing and reduce voids, aiding in smoother flow. Addition to Alkaline Activation ($\text{NaOH} + \text{Na}_2\text{SiO}_3$) promotes dissolution of aluminosilicate phases, enhancing paste cohesion and rheology.

The most notable performance was observed in the TL-2P/10I/M8 mix, which achieved a slump of 90 mm, representing a 100% increase over the control mix (C). This improvement is attributed to the synergistic effect of surface treatment and optimal PEG400 dosage, which enhanced particle dispersion and reduced internal friction. These findings underscore the effectiveness of treated LECA and tailored additive combinations in producing highly workable lightweight geopolymer concrete. Finally, TL-2P/10I/M8 shows the best workability, doubling the slump compared to the control mix. This suggests optimal synergy between treated LECA, PEG400, and iron oxide under the given alkaline activation.

Generally, the slump results indicate that both the surface treatment of LECA and the addition of PEG400 significantly improve workability, not only by increasing slump but also through underlying mechanisms. Surface treatment reduces the water absorption of the porous LECA, preserving free water in the mix, while PEG400, acting as a surfactant, lowers surface tension and enhances particle dispersion, reducing internal friction. The optimal performance observed at 2% PEG400 and 10% iron oxide reflects a synergistic balance between improved plasticization, enhanced particle packing, and controlled water demand. Consequently, the treated LECA and modified mix maintain consistency and fluidity, leading to a 100% increase in slump compared to the control. This demonstrates that such geopolymer lightweight concrete mixtures can achieve high workability without compromising stability, making them suitable for applications requiring high flowability, such as pumped concrete and complex formworks.

4.2. Density

Related to density results shown in Figure 9 and previously slump results in Figure 9, the TL-2P/10I/M8 mix achieved the highest slump value of 90 mm, representing a 100% increase over the control mix, highlighting its superior rheological behavior. In terms of density, treated mixes showed modest but consistent gains of 0.72% to 1.59% over untreated counterparts, attributed to enhanced interfacial bonding and reduced porosity. The TL-3P/20I/M8 mix exhibited the highest target density of 1280 kg/m^3 , marking a 1.83% increase compared to the control. These findings confirm the synergistic effect of LECA surface treatment and additive optimization in producing lightweight concrete with improved mechanical and thermal characteristics. Also, the mix TL-3P/20I/M8 outperformed the control mix by 1.83%, indicating superior compaction and reduced porosity due to the synergistic effect of surface treatment, PEG400, and iron oxide.

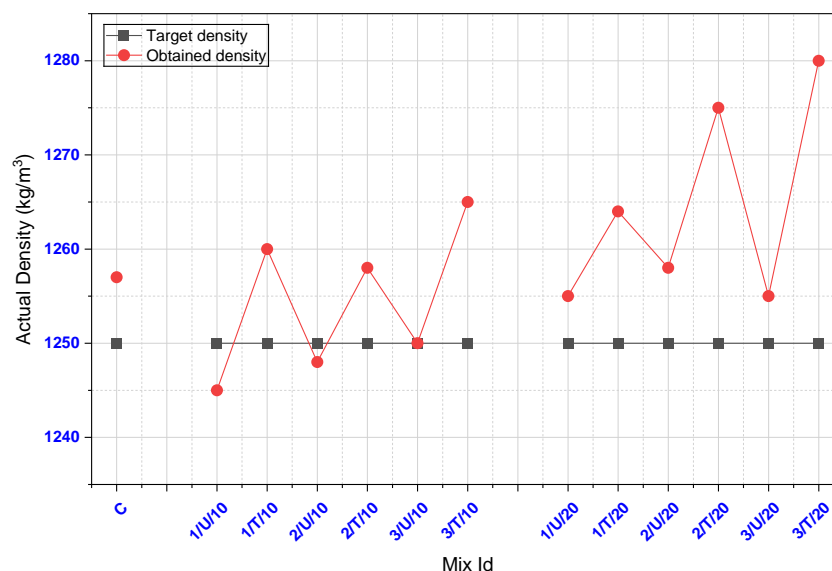


Figure 10. Comparing the target and actual densities for LECA Lightweight Concrete with Iron Oxide/PEG400 mixtures

Surface treatment of LECA also enhances the bond between aggregate and matrix, reducing interfacial voids and improving packing efficiency. Iron Oxide Addition Contributes to matrix densification due to its fine particle size and filler effect. Alkaline activation can introduce and facilitate geopolymer gel formation, improving microstructure compactness. These factors collectively reduce porosity and improve the homogeneity of the mix, resulting in higher density values.

4.3. Water Absorption

From Figure 11, surface treatment (likely acid washing, thermal treatment, or silane coupling) reduces the surface porosity and hydrophilicity of LECA aggregates. This leads to an improved interfacial transition zone (ITZ) between the LECA and the geopolymer matrix, reducing microcracks and capillary pores. Better geopolymer paste penetration into the aggregate surface creates a denser, more impermeable matrix that restricts water ingress. Treated LECA has lower inherent water absorption, which means the aggregate itself absorbs less water, contributing to lower overall mix absorption. According to PEG400, it acts as a plasticizer and pore blocker; it improves workability without increasing water content, leading to reduced capillary porosity. Higher PEG content (up to 3%) enhances pore refinement and may form hydrophobic films on pore surfaces, resisting water penetration. PEG can also improve geopolymerization kinetics, resulting in a more complete reaction and fewer unreacted particles that could absorb water. On the other hand, iron oxide particles are fine and non-porous, acting as micro-fillers that improve particle packing density. At 20% content, iron oxide reduces total porosity and blocks capillary channels, creating a tortuous path for water penetration. Iron oxide may also participate in geopolymer reactions, forming additional cementitious compounds that seal micro-pores.

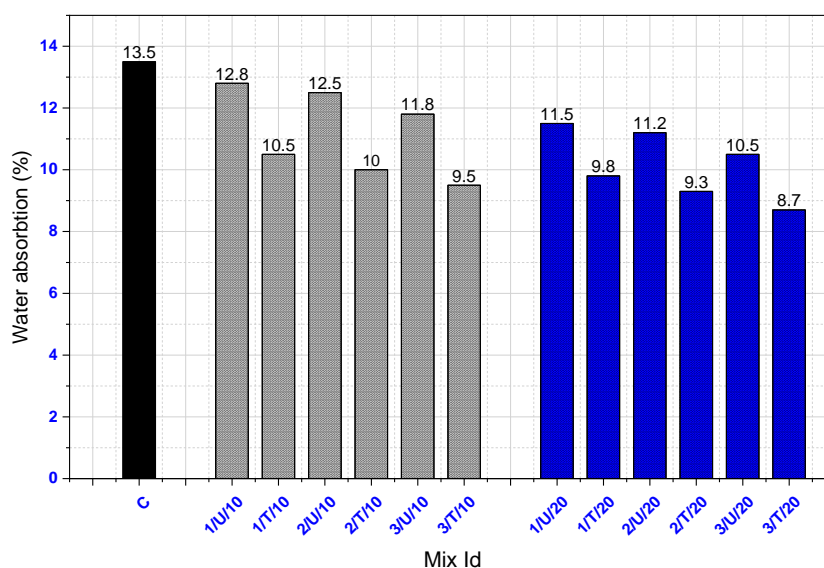


Figure 11. Water Absorption for LECA Lightweight Concrete with Iron Oxide/PEG400 mixtures

Also, Surface treatment of LECA consistently reduces water absorption by 15–20% compared to untreated LECA. Increasing PEG400 content progressively reduces water absorption (optimal at 3% for lowest absorption). Higher iron oxide content (20%) further reduces water absorption compared to 10%, due to improved particle packing and pore blocking. All geopolymer-enhanced mixes show significantly lower water absorption than control, confirming their superior durability characteristics. “TL-3P/20I/M8” is ideal for applications requiring high durability and moisture resistance (e.g., exterior cladding, marine structures, foundations). The combination of treated LECA + high PEG400 + high iron oxide creates a synergistic effect that maximizes pore refinement and hydrophobicity. The 35.56% reduction in water absorption will represent a significant improvement in concrete durability, potentially extending service life in aggressive environments.

The water absorption results confirm that treated LECA + 3% PEG400 + 20% iron oxide provides the lowest water absorption in this geopolymer lightweight concrete system, with a 35.56% improvement over conventional LECA concrete. This enhancement is attributed to optimized pore structure, improved interfacial bonding, efficient particle packing, and potential hydrophobic effects, making it ideal for durable, moisture-resistant lightweight construction applications.

Also, it's noticed that surface treatment limits the aggregate's water uptake by reducing its “sponge effect,” while PEG400 forms a thin polymeric layer within pore walls, decreasing capillary suction. Additionally, iron oxide acts as a micro-filler that refines pore size distribution and lowers overall porosity, with 20% dosage proving more effective than 10% due to improved packing density. The observed 35.6% reduction in water absorption reflects enhanced durability by limiting the ingress of harmful agents such as chlorides and sulfates, making the material more suitable for aggressive environments. A slight increase in absorption at lower iron oxide content highlights the importance of optimal dosage for maximizing pore refinement and performance.

4.4. Splitting Tensile Strength vs. Compressive Strength

The compressive stress test was performed on the standard samples as shown in Figures 12-a and 12-b. The test results demonstrate significant mechanical enhancement in LECA lightweight concrete through geopolymer reinforcement with iron oxide and PEG400 (see Figure 13). Surface treatment of LECA aggregates consistently improves both compressive and splitting tensile strength across all mixes. For compressive strength, treated samples show increases of 9.7–19.5% over untreated counterparts, with TL-3P/20I/M8 achieving the highest compressive strength of 45 MPa (73.1% above control). Similarly, splitting tensile strength improves by 10.3–18.2% with treatment, reaching 4.0 MPa (73.9% above control) in the same optimal mix. This strength enhancement correlates directly with the previously observed improvements in workability (slump) and reductions in water absorption and density. The scientific basis for these improvements lies in the surface treatment creating a stronger interfacial transition zone (ITZ) between the geopolymer matrix and LECA aggregates, reducing microcracks and improving load transfer. Additionally, PEG400 optimizes particle dispersion and workability without compromising the geo-polymerization process, while iron oxide acts as a micro-filler that enhances particle packing density and participates in secondary cementitious reactions.

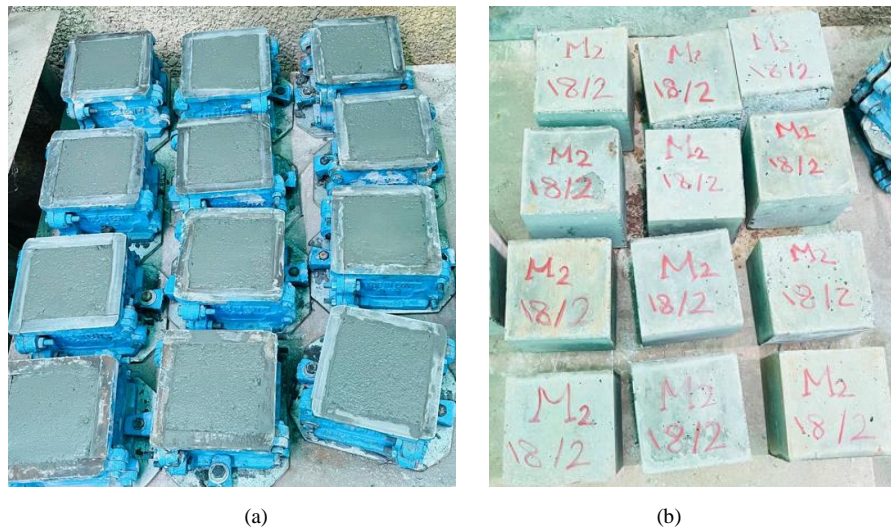


Figure 12. LECA concrete mixtures after being poured into standard cubes, (b) Cubes after being removed from standard Molds, before testing, and after curing

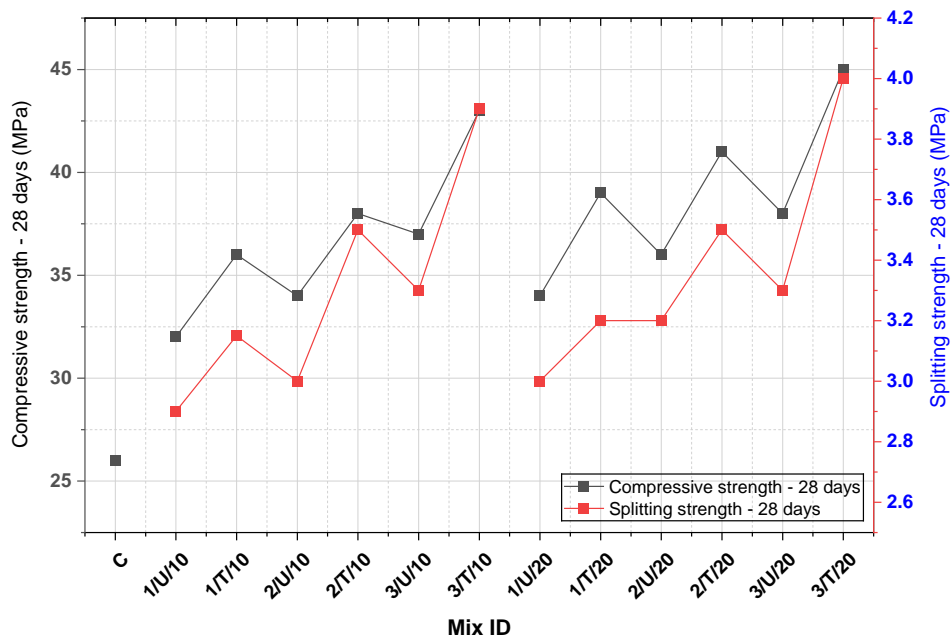


Figure 13. Compressive strength Vs splitting tensile strength of LECA Lightweight Concrete with Iron Oxide/PEG400 mixtures

The correlation between increased strength and reduced water absorption is particularly significant: mixes with lower water absorption (TL-3P/20I/M8 at 8.7%) demonstrate the highest mechanical performance, indicating that the denser, more impermeable microstructure created by treated LECA, optimal PEG400 dosage (3%), and higher iron oxide content (20%) directly contributes to enhanced load-bearing capacity. The simultaneous improvement in slump (90 mm in TL-2P/10I/M8) suggests that workability enhancements do not come at the expense of mechanical properties when proper mix design is implemented.

The optimal mix based on both compressive and splitting tensile strength is TL-3P/20I/M8, which demonstrates Compressive strength: 45 MPa (73.1% increase over control's 26 MPa), Splitting tensile strength: 4.0 MPa (73.9% increase over control's 2.3 MPa), Water absorption: 8.7% (35.6% reduction from control's 13.5%) and Target density reduction of 35.6% from control. This mix represents an optimal balance where surface treatment, PEG400 plasticization, and iron oxide reinforcement create a synergistic effect: treated LECA improves bond strength, PEG400 ensures proper workability and pore refinement, and iron oxide enhances matrix density and reactivity. The result is a lightweight concrete with superior mechanical properties, reduced permeability, and improved durability—making it suitable for structural applications where both strength and weight reduction are critical.

4.5. Bulk Electrical Resistivity (BER)

From Table 8, the bulk electrical resistivity (BER) results demonstrate that geopolymer reinforcement with iron oxide and PEG400 significantly enhances the electrical resistance of LECA lightweight concrete over time, indicating improved durability and reduced permeability. Surface treatment of LECA aggregates consistently increases BER values across all curing ages, with treated samples showing 15.4–29.8% higher resistivity than untreated counterparts at 28 days.

Table 8. Results of bulk electrical resistivity (BER)

Mix Id	Mix. Designation	3 days	7 days	14 days	21 days	28 days	45 days	56 days	90 days
		(K Ω - cm)							
C	CML	4.1	5.3	6.1	6.9	7.4	9.0	10.2	12.5
1/U/10	UL-1P/10I/M8	5.2	7.1	8.5	9.8	11.1	13.9	15.3	18.8
1/T/10	TL-1P/10I/M8	6.4	8.6	10.2	12.1	13.8	16.5	18.3	22.6
2/U/10	UL-2P/10I/M8	5.8	7.9	9.7	11.2	12.9	15.8	17.2	21.0
2/T/10	TL-2P/10I/M8	7.0	9.5	11.5	13.6	15.4	18.3	20.1	24.8
3/U/10	UL-3P/10I/M8	6.1	8.3	10.1	11.7	13.5	16.4	17.8	22.1
3/T/10	TL-3P/10I/M8	7.5	10.1	12.3	14.7	16.5	19.4	21.0	25.9
1/U/20	UL-1P/20I/M8	5.5	7.6	9.2	10.8	12.5	15.1	16.7	20.5
1/T/20	TL-1P/20I/M8	6.9	9.2	11.0	13.0	14.9	17.8	19.4	23.7
2/U/20	UL-2P/20I/M8	6.0	8.1	9.9	11.6	13.3	16.0	17.5	21.9
2/T/20	TL-2P/20I/M8	7.3	9.8	11.8	13.8	15.6	18.4	20.2	25.0
3/U/20	UL-3P/20I/M8	6.4	8.7	10.4	12.3	14.1	17.0	18.6	22.9
3/T/20	TL-3P/20I/M8	7.8	10.5	12.7	14.9	16.8	19.6	21.5	26.4

As shown in Figure 14, specifically, TL-3P/20I/M8 achieves the highest resistivity of 16.8 k Ω ·cm at 28 days (127% above control) and 26.4 k Ω ·cm at 90 days (111% above control). This improvement correlates directly with previously observed reductions in water absorption (35.6% lower than control for the same mix) and increases in compressive strength (73.1% above control). The scientific basis for this correlation lies in the denser, less permeable microstructure created by treated LECA aggregates, which reduces pore connectivity and limits ionic transport paths through the concrete matrix. The synergistic combination of treated LECA (improved ITZ), optimal PEG400 dosage (3% for pore refinement), and higher iron oxide content (20% for micro-filling and pozzolanic activity) creates a composite with fewer interconnected pores and reduced capillary porosity, thereby increasing electrical resistance as an indirect measure of durability.

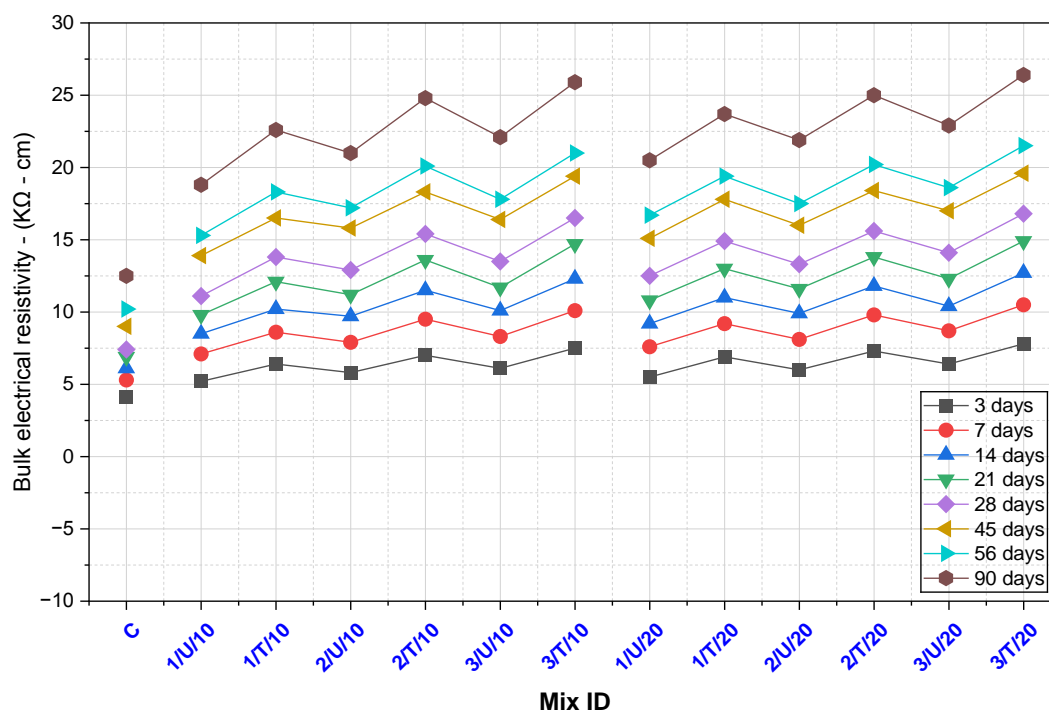


Figure 14. Bulk electrical resistivity (BER) of LECA Lightweight Concrete with Iron Oxide/PEG400 mixtures for 3, 7, 14, 21, 28, 45, 56 and 90 days

The progressive increase in BER with curing time (from 3 to 90 days) indicates continued geo-polymerization and microstructural densification, with treated samples maintaining a consistent advantage over untreated ones throughout the curing period. This trend confirms that the enhanced matrix integrity from surface treatment not only improves early-age properties but also supports long-term durability development. The strong positive correlation between higher BER values and lower water absorption (e.g., TL-3P/20I/M8 with 8.7% absorption and 16.8 kΩ·cm resistivity at 28 days) demonstrates that the same microstructural features that limit water ingress also restrict ionic movement, making BER a reliable indicator of both permeability reduction and corrosion resistance.

The optimal mix based on BER performance is TL-3P/20I/M8, which demonstrates at 28 days with 16.8 kΩ·cm (127% increase over control's 7.4 kΩ·cm) and 90 days with 26.4 kΩ·cm (111% increase over control's 12.5 kΩ·cm) related to its compressive strength: 45 MPa (73.1% above control) and water absorption: 8.7% (35.6% below control), this mix represents the optimal balance between mechanical enhancement, permeability reduction, and durability improvement, with the high BER values indicating excellent corrosion resistance and long-term stability—making it particularly suitable for applications in aggressive environments where both structural performance and durability are critical.

Generally, the bulk electrical resistivity (BER) results reveal significant improvements in microstructural development and durability over time for treated mixes. Even at early ages, higher resistivity values indicate accelerated pore refinement due to surface treatment and additives, with this advantage increasing at later ages as continued geopolymerization enhances densification. All treated mixes exceed the corrosion protection threshold (12 kΩ·cm) by 28 days, with the optimal mix reaching values associated with negligible corrosion risk by 90 days, highlighting its suitability for reinforced concrete applications. The increased resistivity is attributed to reduced pore connectivity, lower ionic mobility, and the influence of iron oxide on pore solution chemistry. Additionally, the consistent ranking of resistivity values across all curing ages confirms a systematic, dosage-dependent improvement rather than random variation.

5. Comparison with Previous Studies

As shown in Table 9, the comparison with previous studies reveals that the present work achieves superior or comparable performance across all evaluated properties through the synergistic combination of LECA surface treatment, PEG-400 incorporation, and iron oxide addition within a geopolymer matrix. While previous studies on LECA-based geopolymer concrete reported significant reductions in compressive and tensile strengths (up to 50% decrease with 100% LECA replacement), the present study achieved a 73.1% increase in compressive strength (45 MPa) relative to the control mix, demonstrating that surface treatment effectively mitigates the typical strength penalties associated with

lightweight aggregates. Regarding PEG-400 utilization, earlier investigations identified optimal dosages of 0.5–1% for self-curing concrete; however, the present study achieved optimal performance at 3% PEG-400, attributed to the combined effects of surface treatment and geopolymer activation, which enhanced workability (90 mm slump) without compromising strength. For iron oxide reinforcement, recent studies have demonstrated that 30% nano-Fe₂O₃ content improves elastic properties by up to 60%, corroborating the present finding that 20% Fe₂O₃ contributes to microstructural densification and reduced water absorption (8.7%). Furthermore, the bulk electrical resistivity (16.8 kΩ·cm at 28 days) substantially exceeds values reported for LECA-based pervious concrete (6.84–11.45 kΩ·cm), indicating superior durability and corrosion resistance. Overall, the present study advances lightweight geopolymer concrete technology by demonstrating that treated LECA combined with 3% PEG-400 and 20% iron oxide yields mechanical and durability properties that exceed both conventional LECA concrete and previously reported lightweight geopolymer systems, while maintaining the sustainability benefits of reduced cement utilization and industrial waste vaporization.

Table 9. The most significant results from earlier research

Property	Present Study (Optimal Mix: TL-3P/20I/M8)	Previous Study Results	Comparison / Trend	Reference
Compressive Strength (MPa)	45.0 (28 days)	47.87 (M30 grade, 0.5% PEG-400)	Present study achieved comparable strength with higher LECA content (100%) and geopolymer system	[57]
		43.8 (90 days, basalt-pumice LWC)	Present study achieved higher strength at 28 days	[41, 58]
		53.6 (Brazilian LWC)	Present study slightly lower but with fully lightweight aggregate replacement	[18]
Splitting Tensile Strength (MPa)	4.0 (28 days)	~2.5 (LWGPC with 100% LECA)	Present study shows ~60% higher tensile strength than conventional LECA geopolymer concrete	[8, 58, 59]
Water Absorption (%)	8.7	18.0 (LECA aggregate typical)	Present study achieved 52% reduction in water absorption compared to untreated LECA	[3]
		11.185–12.695 (LECA pervious concrete)	Present study shows lower absorption despite higher strength	[4, 9, 41, 58]
Density (kg/m ³)	1280	800–1860 (range for LECA concrete)	Present study within typical range for structural lightweight concrete	[58]
Bulk Electrical Resistivity (kΩ·cm)	16.8 (28 days)	6.84–11.45 (LECA pervious concrete, 28 days)	Present study achieved significantly higher resistivity (47–146% improvement)	[9, 41]
Iron Oxide Effect	20% Fe ₂ O ₃ with 3% PEG-400	30% nano-Fe ₂ O ₃ improved elastic properties by 60%	Both studies confirm Fe ₂ O ₃ enhances mechanical properties at optimal dosages (20–30%)	[57, 58]
PEG-400 Optimal Dosage	3% (with surface treatment)	0.5–1% (for conventional concrete)	Present study achieved higher optimal dosage due to synergistic effect with surface treatment and geopolymer matrix	[2, 9, 41]

6. Conclusions

This comprehensive experimental study conclusively demonstrates that the geopolymer enhancement of lightweight LECA concrete using iron oxide and PEG400, combined with surface treatment of the LECA aggregates, results in a superior composite material with significantly enhanced mechanical, durability, and workability properties.

- The surface treatment of LECA aggregates proved to be a pivotal factor, consistently improving the interfacial transition zone (ITZ) and leading to substantial gains across all tested parameters.
- The optimal mix, TL-3P/20I/M8 (treated LECA with 3% PEG400 and 20% iron oxide), emerged as the top performer, showcasing an exceptional balance of properties. It achieved a compressive strength of 45 MPa and a splitting tensile strength of 4.0 MPa, representing increases of 73.1% and 73.9%, respectively, over the control mix, while simultaneously reducing water absorption by 35.6%.
- This mechanical enhancement is directly correlated with a denser, less permeable microstructure, as evidenced by a 127% increase in 28-day bulk electrical resistivity, which forecasts excellent long-term durability and corrosion resistance.
- Furthermore, the research confirms that workability is not sacrificed for strength; the TL-2P/10I/M8 mix exhibited a 100% increase in slump, highlighting the effectiveness of PEG400 as a plasticizer and the importance of tailored mix design. In summary, the synergistic integration of treated LECA, an optimal dosage of PEG400 (3%), and a higher iron oxide content (20%) within an alkaline-activated geopolymer matrix produces a structurally efficient, durable, and highly workable lightweight concrete.
- This advanced material is ideally suited for sustainable construction applications where reduced weight, enhanced mechanical performance, and superior resistance to aggressive environments are critical requirements.

7. Abbreviations

PEG400	Polyethylene glycol 400	LECA	Lightweight expanded clay aggregate
BER	Bulk electrical resistivity	Fe ₂ O ₃	Iron oxide
LWC	Lightweight concrete	GPC	Geopolymer concrete
LWAC	Lightweight aggregate concrete	LWGPC	Light weight geopolymer concrete
NSC	Normal-strength concrete	EPW	Expanded clay production waste
EPWCA	Expanded clay production waste coarse aggregate	NIOP	Nano iron oxide particles
SsF	Sisal fiber	ELMs	Engineered living materials
RHA	Rice husk ash		

8. Declarations

8.1. Author Contributions

Conceptualization, H.M.A., A.A.A.A., and A.A.; methodology, M.F., A.A.N., and H.M.A.; formal analysis, A.A. and M.F.; data curation, A.A.A.A., H.M.A., and M.F.; writing—original draft preparation, A.A.A.A. and M.F.; writing—review and editing, A.A.A.A. and H.M.A.; supervision, A.A.A.A., A.A., and A.A.N. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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