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SUSTAINABLE LIGHTWEIGHT CONCRETE PRODUCED USING WASTE GLASS POWDER: MECHANICAL PROPERTIES AND MICROSTRUCTURE

ATIK CAM TOZU KULLANILARAK ÜRETİLEN SÜRDÜRÜLEBİLİR HAFİF BETON: MEKANİK ÖZELLİKLER VE MİKRO YAPI

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ABSTRACT

This study investigates the use of glass powder (GP) as a sustainable alternative to cement in the production of lightweight concrete, addressing the environmental footprint reduction and waste management of traditional concrete materials. In this study, 8 different concrete series were produced by substituting CT with cement in varying ratios. The produced samples were cured using standard methods and kept in $MgSO_4$ and Na_2SO_4 solutions for specific periods of time, and their mechanical performance and microstructural properties were evaluated. As a result of the tests performed on the concrete specimens obtained, it was found that 5% and 10% GP substitution provided maximum performance. The originality of the study is the feasibility of reducing the amount of cement while maintaining the performance of lightweight concrete and it is thought to contribute significantly to sustainability studies. In addition, the use of GP in concrete production reduces material weight, contributes to sustainable construction practices and offers a viable alternative in lightweight concrete production.

Keywords: Glass powder, sustainability, environmental footprint, lightweight concrete

ÖZET

Bu çalışma, hafif beton üretiminde çimentoya sürdürülebilir bir alternatif olarak cam tozu (CT) kullanımını araştırarak, geleneksel beton malzemelerin çevresel ayak izinin azaltılması ve atık yönetimi konularını ele almaktadır. Çalışmada, çimento ile farklı oranlarda CT ikame edilerek 8 farklı beton serisi üretilmiş, üretilen numuneler standart kür ile $MgSO_4$ ve Na_2SO_4 çözeltisinde belirli süreler boyunca bekletilmiş ve bu numunelerin mekanik performansları ve mikro yapısal özellikleri değerlendirilmiştir. Elde edilen beton numuneler üzerinde yapılan testlerin sonucunda, %5 ve %10 CT ikamesi ile maksimum performans elde edildiği bulunmuştur. Çalışmanın özgünlüğü, hafif betonun performansını korurken çimento miktarını azaltmanın uygulanabilirliğidir ve sürdürülebilirlik çalışmalarına önemli katkı sağlayacağı düşünülmektedir. Ayrıca, beton üretiminde CT kullanımı malzeme ağırlığını azaltmakta, sürdürülebilir inşaat uygulamalarına katkıda bulunmakta ve hafif beton üretiminde uygulanabilir bir alternatif sunmaktadır.

Anahtar Kelimeler: Cam tozu, sürdürülebilirlik, çevresel ayak izi, hafif beton

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INTRODUCTION

High carbon emissions in the materials industry are seen as the primary cause of global warming (Xuan et al., 2020). Cement production in the construction sector is a major source of carbon emissions. Namely, annual carbon emissions from cement production account for about 8% of global carbon emissions (Liu et al., 2025). This situation also leads to environmental crises. Therefore, the development of materials that minimize resource consumption and have a more environmentally friendly effect in the construction sector is an important research topic that cannot be ignored. One of these research topics is to contribute to sustainability (Ganesh & Muthukannan, 2020; Singhal et al., 2021). Alsaif stated that CO_2 emissions from cement production have a negative impact on the climate and researched the performance of concrete by substituting cement with ceramic waste powder to reduce the amount of cement. As a result of the study, he observed that substituting cement with ceramic waste powder was not significantly effective and that the improvement was low, up to a 20% substitution rate.
(Alsaif, 2021). On the other hand, a study on red ceramic waste indicated that the use of cement and red ceramic waste can reduce CO_2 emissions (Hoppe Filho et al., 2021).

Industrial waste is widely used as an alternative to cement in concrete production. (Wu et al., 2018). One of these materials is glass Powder (GP). Traditionally, some of the GP can be recycled. (Derinpinar et al., 2022; Paul et al., 2022). Most of the remaining GP is landfilled. The part that cannot be recycled takes up a significant amount of space and this storage problem creates environmental pollution (Jain et al., 2020), (Demir et al., 2022).

With the advancement of industrialization and urbanization, the recycling process of GP materials is becoming more difficult. For example, in the United States, up to 52.9% of glass containers have to be thrown into landfills. This not only leads to increased disposal costs, but also to pollution and waste of land resources (Miao et al., 2024), (Demir & Alyamaç, 2022). Glass powder needs to be melted at temperatures between 1200 and 1400 ◦C for recycling. Due to color separation and high cleaning costs, only a small fraction of GP is recycled by certain sectors such as container manufacturers (Ishaq et al., 2025; Turkey et al., 2022). On the other hand, its chemical properties make it unsuitable for storage on soil. For these reasons, many studies have been conducted for the use of GP in different areas (Paul et al., 2022; Raju & Kumar, 2014). In the studies carried out, if glass powder is used in concrete, both the cost and time concept is reduced to lower values and the storage problem is eliminated. Thus, environmental gains are also provided. In addition, the use of glass powder in concrete provides economic benefits and expands its range of applications. Incorporating GP into concrete production is an attractive strategy that effectively manages glass waste and offers significant environmental benefits (Bisikirske et al., 2019).

The materials used as pozzolan in the concrete industry must have an amorphous structure and be fine-grained in order to show sufficient activity (Gözet, 2024). In the studies conducted, it was determined that the use of glass powder with a diameter of 38 μm in concrete showed pozzolanic effect (Çınar et al., 2020). Glass powder with a particle size of 0.038-0.075 mm, which has pozzolanic properties, is used as an alternative cement complementary material to obtain the desired performance from concrete (Ulucan & Alyamac, 2023). As a result of the pozzolanic activity of GP, it forms calcium silicate hydrate (C-S-H) gels that give strength to concrete (Osfouri et al., 2025).

Recently, various types of concrete have been produced by using lightweight aggregates and substituting cement with waste materials. One of the most widely produced of these is lightweight concrete. Lightweight concretes are promising due to their potential to reduce structural loads, reduced bulk density, thermal insulation properties and adaptability to specific construction requirements (Osfouri et al., 2025). Since approximately 80% of concrete consists of aggregates, the most common method of producing lightweight concrete is to use voided lightweight aggregates (Hamada et al., 2022). Lightweight aggregates can be obtained naturally, but can also be produced from natural materials or industrial by-products (Shang et al., 2024). Pumice (acidic/basaltic), diatomite, tuff and volcanic slag are in the natural aggregates group, while all light aggregates except diatomite are volcanic aggregates (Lin et al., 2023). Lightweight aggregates have lower unit weight than normal aggregates due to their porous structure. Therefore, lightweight concretes produced with lightweight aggregates have weaker mechanical properties. In order to minimize this disadvantage, mechanical properties are improved by using certain amounts of mineral additives

such as GP powder, fly ash, silica fume, etc. GP powders contain high levels of silicate and are considered as pozzolanic materials that can be used in concrete (Dündar et al., 2020).

The fact that the amount of GP is increasing day by day, the storage problem of these materials, the environmental concerns and the high cost of the recycling process lead researchers to search for solutions for the use of this material in different areas. In this study, the mechanical properties and microstructure of environmentally friendly lightweight concretes produced using GP powder and pumice aggregate were investigated. For this purpose, a total of 9 lightweight concrete series were prepared, including 1 control series. The lightweight structural concretes were subjected to mechanical tests at different ages under appropriate curing conditions. Compressive strength (f_c), splitting tensile strength (f_t), porosity (p), ultrasonic pulse velocity (UPV), SEM analysis, sulfate effect - length change relationship were investigated. As a result of the study, compressive strength values higher than the compressive strength limit value of lightweight concrete specified in TS 2511 standard were obtained in all of the concrete specimens produced. In the sulfate test, the best compressive strength values were obtained in 5% series regardless of sulfate type. The flow diagram of the study is presented in Figure 1.

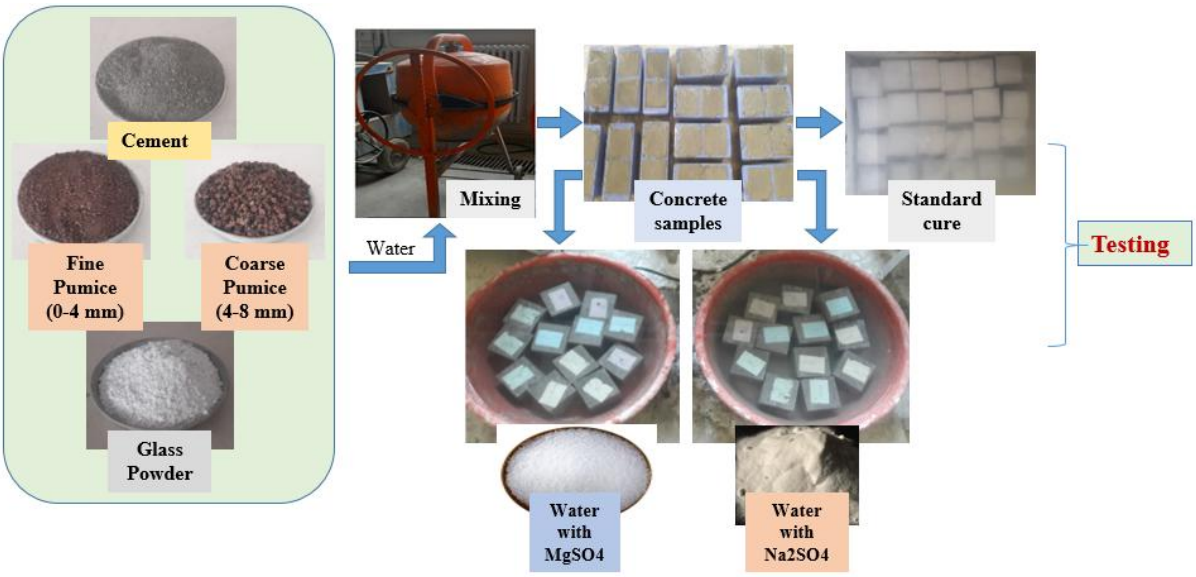


Figure 1. Flow Chart of the Study

MATERIAL AND METHOD

The cement used herein was ordinary Portland cement designated as grade 42.5 R MPa and was produced by a local cement manufacturer in Elazıg and satisfied the requirements of TS EN 197-1 [24]. The chemical composition of cement and GP are given in Table 1. Furthermore, the specific gravity and water absorption values for pumice aggregate are 1,062 (g/cm³) and 11,33 (%) for fine pumice (0-4 mm), and 0,822 (g/cm³) and 14,4 (%) for coarse pumice (4-8 mm), respectively.

Table 1. Chemical Compositions of Cement and GP

Chemical properties	SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	SO_3	Na_2O	K_2O	Specific gravity (g/cm^3)
Cement	20.70	64.70	2.90	5.54	2.74	2.20	0.10	-	3.00
GP	70.06	11.52	1.29	0.78	-	0.24	12.88	0.31	2.65

Figure 2 presents the size distribution of the used basaltic pumice aggregate. Curves A16, B16, and C16 represent the limiting values for the aggregate particle size distribution curve specified in TS802 for concrete with a maximum aggregate particle size of 16.0 mm (TS802, 2016).

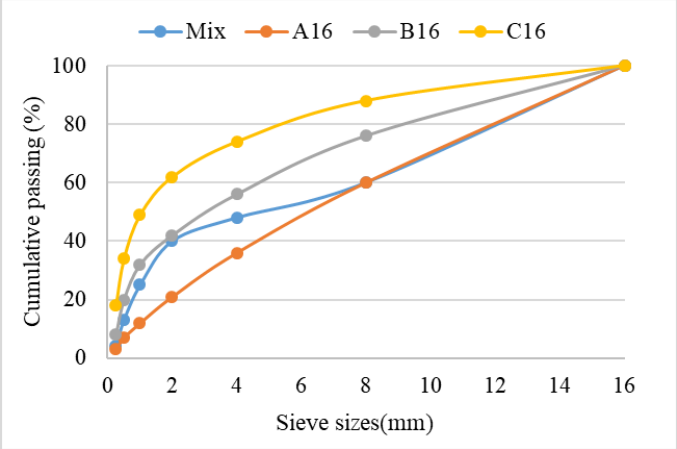


Figure 2. Particle Size Distribution.

Mix Proportion

In order to determine the strength and durability properties of lightweight concretes produced using GP and pumice aggregate, a total of 9 concrete series were prepared and tested, one of which was a control series. In the mixtures, GP was substituted with cement in different proportions by weight. Mix proportions are presented in Table 2. In the series coded as LWC-GP, LWC represents lightweight concrete and GP represents glass powder. The numerical values next to the coding indicate the replacement ratios. For example, LCW-GP5 represents 5% substitution of cement with glass powder.

Table 2. Mixture Design.

Mix Code	Cement	Water	Glass Powder	Fine Aggregate (0-4) mm	Coarse Aggregate (4-8) mm
LWC-GP0	450.0	266.8	0	611	472.7
LWC-GP2.5	438.75	266.8	11.25	611	472.7
LWC-GP5	427.5	266.8	22.5	611	472.7
LWC-GP7.5	416.25	266.8	33.75	611	472.7
LWC-GP10	405.0	266.8	45.0	611	472.7
LWC-GP12.5	393.75	266.8	56.25	611	472.7
LWC-GP15	382.5	266.8	67.5	611	472.7
LWC-GP17.5	371.25	266.8	78.75	611	472.7
LWC-GP20	360.0	266.8	90.0	611	472.7

Casting, Placement and Testing of Concrete Samples

The materials used in preparing the concrete mixtures were weighed on a precision scale. The dry materials were mixed in a mixer for 2 minutes and the mixtures were prepared by adding the mixing water and mixing for another 3 minutes. The unit volume weight of the fresh concrete mixture was determined in accordance with the TS EN 12350-6 standard and the slump values in order to determine its flowability were determined in accordance with the TS EN 12350-2 standard [25], [26]. The prepared concrete mixtures were placed homogeneously in lubricated molds (100×100×100 mm) using a vibration table. The samples were removed from the mold with air pressure after 24 hours. The samples removed from the mold were kept in $MgSO_4$ and Na_2SO_4 solution with normal curing for mechanical tests. Concrete compressive strength test was applied on the 7th and 28th days. Splitting tensile strength, porosity, water absorption and ultrasound transmission speed tests were performed at the end of the 28th day. In addition, SEM analysis was performed to examine the microstructure. Sulfate resistance was determined. Mortar bar

samples with dimensions of 25×25×285 mm were prepared as shown in Figure 3(a). These prepared samples were kept in 5% $MgSO_4$ and Na_2SO_4 solution. Length changes were measured with the 0.01 mm precision comparator given in Figure 3(b) within the scope of the principles specified in the ASTM C1012-87 standard for 150 days as 1,2,3,4,5,8,13,15,17,21. weeks [27]. The length change rates of the series were determined using equation 1.

$$\varepsilon = (\text{Last measurement} - \text{First measurement}) * 0.01/285 * 100 \quad (1)$$

(a) (b)

Figure 3. (a) Comparator (b) Samples of Length Change Test

RESULTS AND DISCUSSION

Compressive Strength

The f_c results of the LWC samples at the end of the 7th and 28th day are shown in Figure 4. When the compressive strength change of lightweight concrete was analyzed, the highest fc value was observed in the control series due to the continuation of hydration with the higher amount of cement. On the other hand, the highest fc value was observed in the LWC-GP10 series at 7 days and in the LWC-GP5 series at 28 days. When the curing time is extended from 7 days to 28 days, the fc value change increases significantly with increasing GP content. The fc values of LWC-GP5 and LWC-GP20 increased by 96.8% and 73.0%, respectively. On the other hand, 28-day fc values decreased with increasing GP substitution rate. The difference between the fc value of the control mixture and the fc values of the GP doped series showed a decreasing trend as the curing time increased. This is thought to be due to the increased pozzolanic reaction (Arslan et al., 2020; Benli, 2019).

According to ACI 213R-14 standard, it is stated that the 28-day compressive strength of structural lightweight concretes to be used structurally should be higher than 21 MPa (*ACI 213R-14, Guide For Structural Lightweight-Aggregate Concrete'*, 2014). Accordingly, 28-day f_c values of all series meet the value specified in ACI 213R-14 standard. Therefore, the use of GP in lightweight concrete will be of great advantage in terms of economic, environmental and sustainability contribution.

Compressive Strength Under the Sulfate Effect

For the determination of sulfate resistance, the specimens were kept in normal water curing and then kept in two different curing waters containing 5% $MgSO_4$ and 5% Na_2SO_4 solutions for 28 days. The fc values of these samples are given in Figure 4. As seen in Figure 4, among the series subjected to 28-day cure in $MgSO_4$ and Na_2SO_4 solutions, the highest fc value was recorded in the LWC-GP5 series exposed to $MgSO_4$ solution. In both solutions, a decrease in fc value was observed in the series after 5% GP additive. In the specimens exposed to sulfate effect, it was determined that the 5% GP added series reached higher strength than the control series. The binding of free lime by the reaction of GP reduces the sulfate effect by reducing the formation of gypsum and the ongoing harmful reactions due to this component (Balapour et al., 2018), (Chen et al., 2018). Therefore, it is observed that the use of GP in concrete increases the resistance of concrete against sulphate.

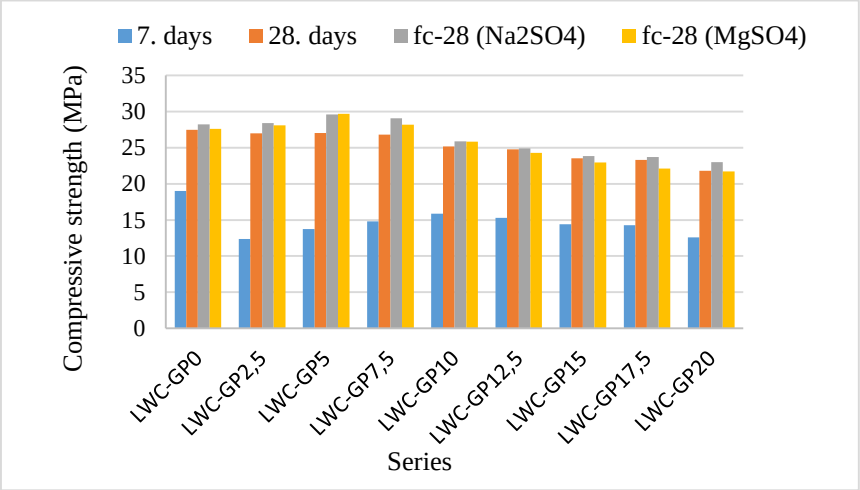


Figure 4. Values of Compressive Strength

Splitting Tensile Strength Before and After Sulphate Effect

In the splitting tensile test, the load increases gradually and micro-cracks are initiated by the contact between the sample and the plates placed in the upper and lower center (*TS EN12390-3, Concrete-Part 3: Hardened Concrete Tests-Determination of Compressive Strength in Test Specimens'*, 2003). When the highest load value is reached, the specimen fractures along the middle line under the effect of tensile stress and a flat fracture surface is obtained (Figure 5).

In Figure 6, when the f_t value of the concrete series with different GP ratios and the control sample before the sulfate effect is examined, it is seen that the highest value is in the LWC-GP10 series. The f_t value of the sample replaced with 10% GP increased by 5.87% compared to the f_t value of the control sample. It is thought that the increase in the f_t value with GP replacement can create a filling effect by filling the gaps between the aggregate and cement paste. It is estimated that the decrease in the f_t value in the GP values above 10% GP replacement is due to the inability of C-S-H gels to form due to the lack of sufficient water in the environment. When the f_t strength is examined after the sulfate effect, it is seen that the highest value is in the LWC-GP5 series (Fig 6). In addition, it was observed that the f_t value was above 4 for all series in the series cured before the sulfate effect, while the f_t value was between values less than 4 in the series cured after the sulfate effect. However, the f_t value of the samples exposed to Na_2SO_4 solution was higher than the f_t value of the samples exposed to $MgSO_4$ solution. This shows that the sulfate resistance of the concrete samples exposed to $MgSO_4$ solution was lower.

Figure 5. Splitting Tensile Strength Test

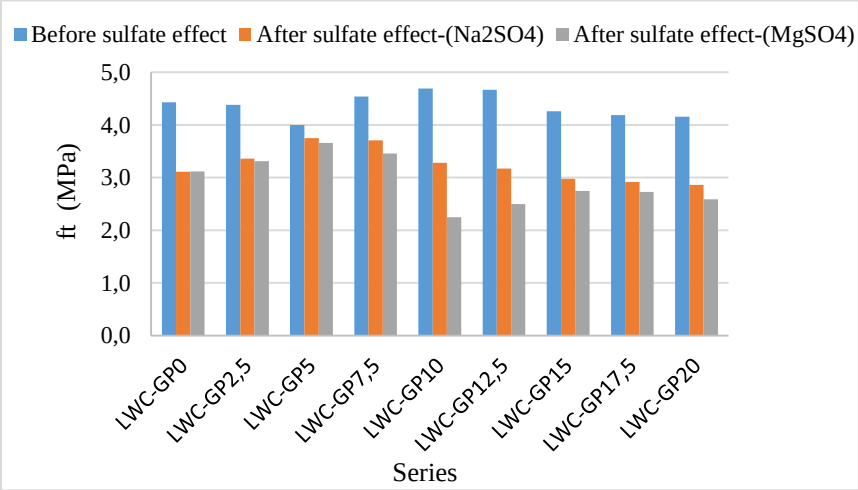


Figure 6. f_t Values Before and After Sulphate Effect

UPV Test Before and After Sulphate Effect

One of the factors in determining the mechanical properties of concrete is the UPV test. With this test, the quality and internal structure of concrete can be evaluated (Zhang et al., 2021). The data of the UPV test results performed in the study are given in Figure 7 before and after the sulfate effect. When the values before the sulfate effect are examined, the highest value is found in the LWC-GP5 series. The fact that the UPV value of the LWC-GP5 series is higher than the control series indicates that there is a decrease in the amount of pores in the concrete and an improvement in its internal structure. According to the suggestion stated by Whitehurst, the concrete quality of the LWC-GP5 series is in the "Good" category, while the other series are in the "Medium" category. The UPV values of the series after the LWC-GP5 series have shown a decreasing trend. It is predicted that this situation is due to the increase in the GP ratio and the insufficient hydration due to the lack of sufficient water in the environment. When the development of UPV values after the sulfate effect is examined, it is seen that the sulfate resistance of the samples exposed to the sulfate solution is high. Approximately 40% of the UPV values of both solutions were in the "Good" concrete category.

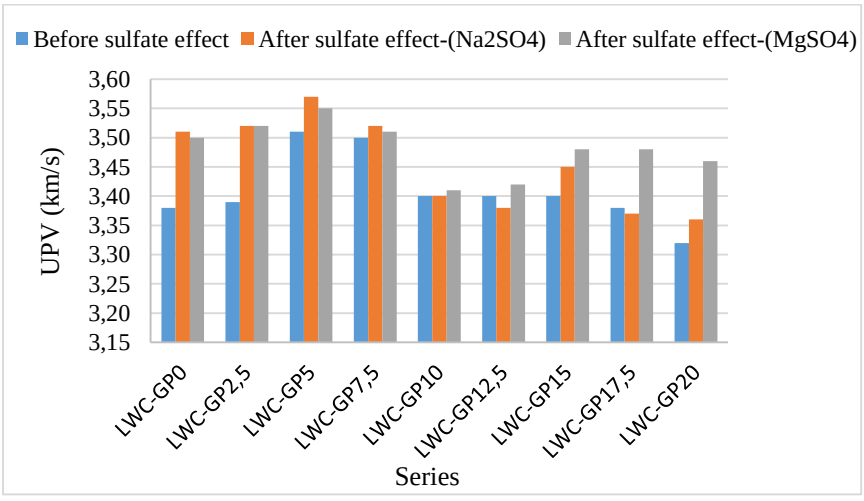


Figure 7. UPV Values Before and After Sulphate Effect

Microstructural properties

Porosity Before and After Sulfate Effect

Porosity value is one of the critical factors in evaluating the durability of hardened concrete. At the end of the 28-day curing period, porosity values before and after sulfate effect varied between 14.09% and 17.63% (Fig 8). In parallel with the increase in UPV values, porosity values naturally decrease.

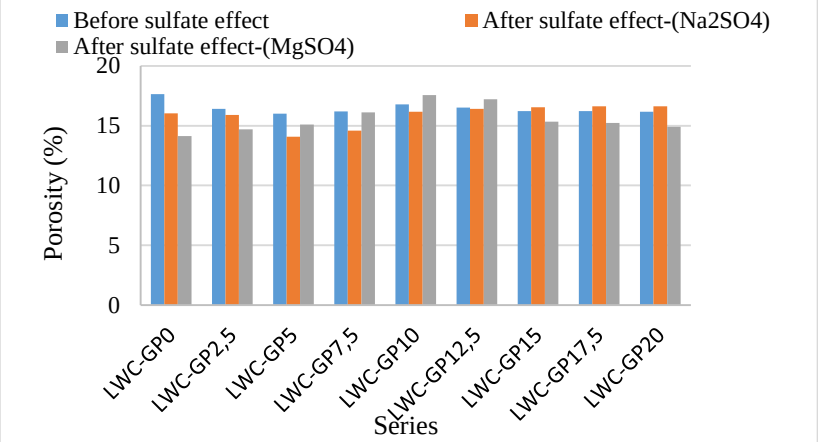


Figure 8. Porosity Values Before and After Sulphate Effect

SEM Investigation of Concrete Samples

Microstructure examination was carried out using scanning electron microscopy (SEM) on sample pieces with maximum mechanical strength at 28 days of age. SEM images of the series are presented in Figure 9.

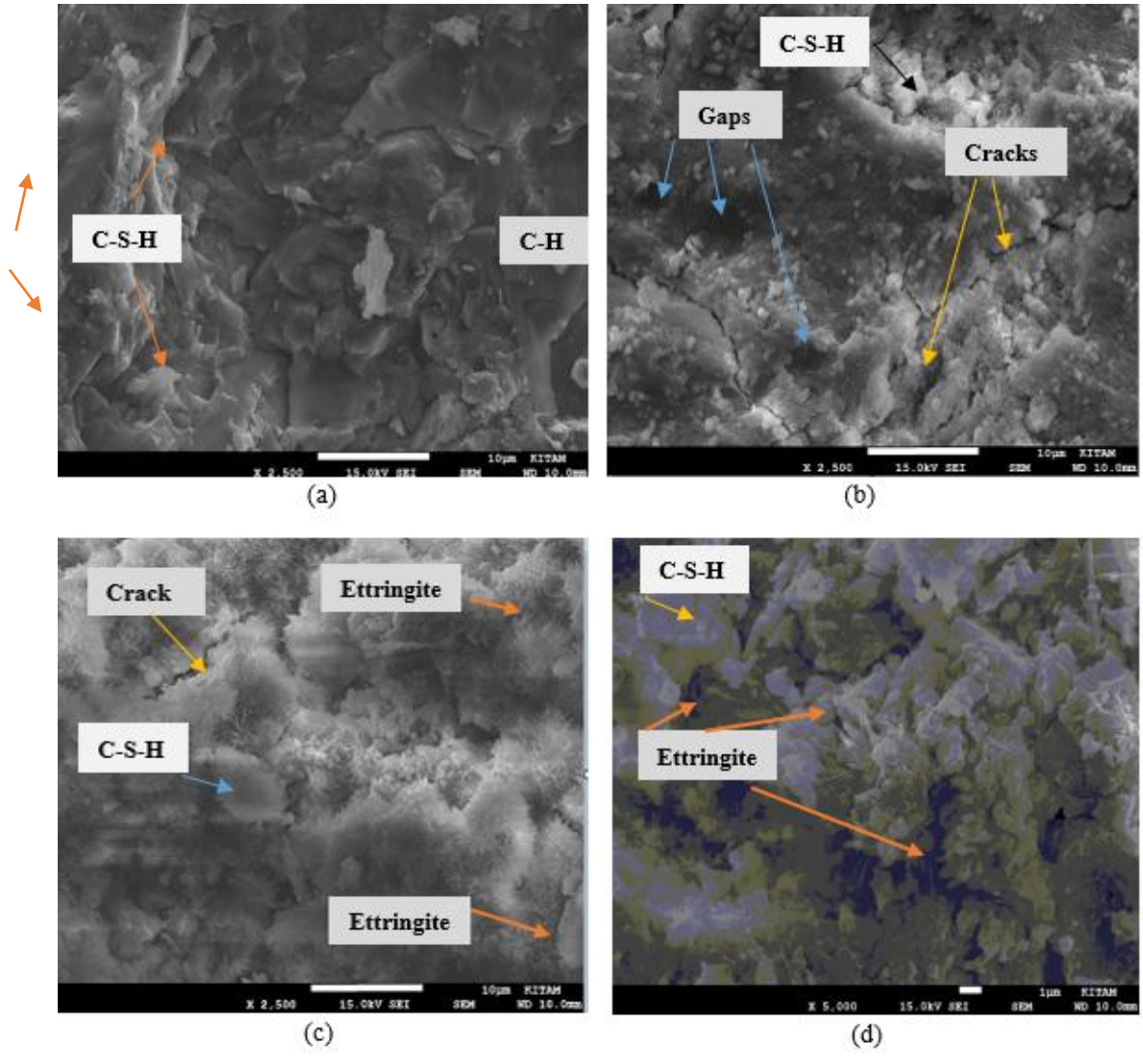


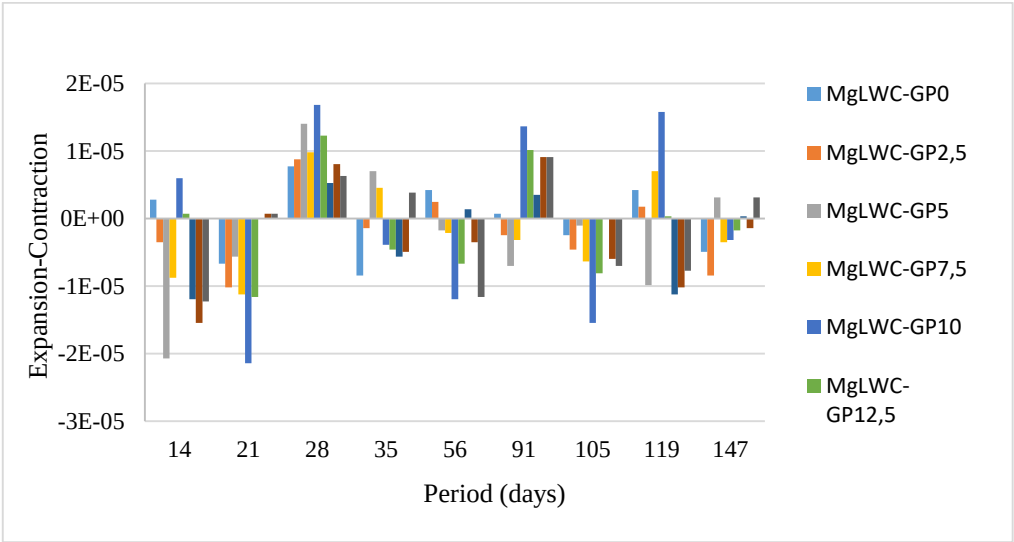
Figure 9. SEM Image of Samples.

Figure 9(a) shows CH and C-S-H. C-S-H (Calcium Silicate Hydrate phase) is the hydration product that provides strength to the concrete with the binding property it gives to the cement. CH (Calcium Hydroxide), which does not have much effect on strength, ensures that the micro environment of concrete is basic. Cracks and voids are clearly seen in Figure 9(b). The specimens with voids form a more porous structure and form a crack-like structure. These defects and cracks adversely affect the mechanical properties of concrete.

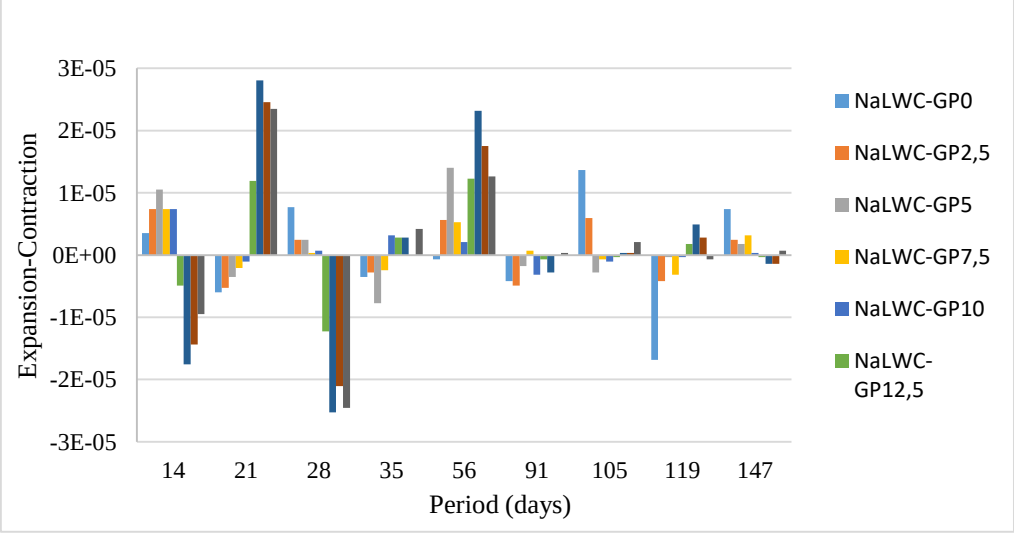
Figure 9(c) shows the formation of ettringite. Etringite is formed as a result of the characteristic reaction of cement hydration reaction and sulphate effect in concrete. The morphology of ettringite depends on the water/cement ratio, sulphate concentration, formation time and age, ambient temperature and humidity [33]. When Figure 9(d) is examined, it is seen that ettringite formation is higher than other samples. This is due to the sample being exposed to sulphate solution.

Expansion and Contraction

One of the tests performed within the scope of the study is the length change test. Length change rates were determined using the equation in equation 1 within the scope of the principles specified in the ASTM C1012-87 standard (*ASTM C1012-87, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*, 2010). The expansion and contraction change graph of length change rates is given in Figure 10.



(a)



(b)

Figure 10. (a) Expansion-Contraction Values in $MgSO_4$ Solution (b) Expansion-Contraction Values in Na_2SO_4 Solution

Positive values in the graph represent expansion and negative values represent contraction. The expansion occurring in cement paste or concrete is called "swelling" or "negative contraction". In all series, a rapid change in size occurred during the first 35 days of exposure to both solutions. Water molecules penetrated between the gel particles and acted as a force opposing the cohesion of these particles, creating a pressure that caused swelling (Leemann et al., 2025). In the following days, the internal pressure caused a smaller change in size due to the formation of ettringite as the number of voids decreased (Colman et al., 2022). Therefore, it can be concluded that the length change observed in the series is a result of the formation of ettringite in the concrete.

4. CONCLUSIONS

Studies on sustainability and recycling in concrete production are increasingly being updated. In particular, the importance of studies aiming to minimize negativities such as unconscious consumption of natural resources, preventing the deterioration of ecological balance, and reducing the greenhouse gas effect released in cement production is increasing. In this study, the strength and durability properties of lightweight load-bearing concretes produced by substituting GP with cement at different ratios were investigated and it was aimed to contribute to the literature by providing significant environmental gains with the substitution of GP with cement. A comprehensive evaluation of lightweight structural concrete produced using pumice aggregate and GP and recommendations are presented below.

- It was observed that the mechanical properties of concrete gradually improved with the increase in GP content up to a certain level. The f_c-7 values varied between 12,38-19,02 MPa. The f_c-28 values showed a decreasing trend with increasing GP content and varied between 21,80-27,48 MPa. In the 28-day water cured specimens containing $MgSO_4$ and Na_2SO_4, the lightweight concrete provides the f_c values and it was determined that the series containing 5% GP powder had the highest compressive strength value and the f_c value decreased as the amount of GP powder increased. Except for the series containing 5% GP powder, the f_c values of the series kept in Na_2SO_4 containing water curing were higher than the f_c values of the series kept in $MgSO_4$ containing water curing. The reason for this is the destruction of C-S-H gels as a result of Magnesium Sulfate attack, resulting in loss of adherence and decrease in strength.
- It was observed that GP added to concrete samples caused a decrease in porosity values. While LWC-GP0 provided the lowest porosity value in the series cured in $MgSO_4$, LWC-GP5 provided the lowest porosity value in the series cured in Na_2SO_4. The low porosity values of the series with GP additives were associated with the finer structure of GP powder than cement.
- In all series exposed to different curing conditions, the series containing 5% GP has the highest UPV value. When the UPV values are compared with the porosity values, the UPV values of the series with low void ratio are higher.
- According to SEM images, the highest ettringite formation is seen in the series containing 5% GP cured in Na_2SO_4 water. The least ettringite formation and void formation is seen in the series containing 15% GP cured in $MgSO_4$ water, which has the lowest expansion.
- By substituting cement with GP in concrete production, waste materials were reused and a significant reduction in the storage problem was achieved. Thus, it was determined that a contribution was made to sustainable development and circular economy.

According to the results obtained from this study, GP powder can be used in lightweight concrete at the tested ratios. Thus, with the use of GP powder, the goal of both environmental and economical concrete production was tried to be achieved by reducing cement consumption.

Conflict of Interest Statement
There is no conflict of interest between the authors.

Statement of Research and Publication Ethics
The study is complied with research and publication ethics

AI Contribution Statement
This article has been written, edited, analyzed, and prepared entirely without the aid of any artificial intelligence tool. I declare that all content, including text, data analysis, and figures, was created solely by the authors.

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