

Production of Environmentally Friendly Foam Concrete Using Waste Material: Effects of Waste Concrete Sludge and Fiber Additives

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Graphical/Tabular Abstract (Grafik Özet)

This study aimed to develop an eco-friendly construction material using waste concrete sludge (CS) as a partial cement replacement and polypropylene fiber (PF) as reinforcement in foam concrete. Mechanical, physical, and thermal properties were evaluated, and performance improvements were observed using CS and PF. / Bu çalışma, köpük betonda çimento yerine atık beton çamuru (CS) ve takviye amacıyla polipropilen lif (PF) kullanarak çevreci bir yapı malzemesi geliştirmeyi hedeflemiştir. Mekanik, fiziksel ve termal özellikler değerlendirilmiş, CS ve PF'in birlikte kullanımıyla performans iyileşmeleri gözlemlenmiştir.



Figure A: Schematic view of foam concrete production containing CS and PF, and properties
/Şekil A: CS ve PF içeren köpük beton üretimi ve özelliklerinin şematik gösterimi

Highlights (Önemli noktalar)

- Waste concrete sludge was partially used instead of cement in foam concrete production to ensure sustainability. / Atık beton çamuru, köpük beton üretiminde çimento yerine kısmen kullanılarak sürdürülebilirlik sağlanmıştır.
- With CS and PF additions, porosity increased while density decreased, improving thermal insulation potential. / CS ve PF katkıları ile gözeneklilik artarken, yoğunluk azalmış; ısı yalıtımı potansiyeli artmıştır.
- Increasing CS content in CS-PF fiber mixtures generally reduced compressive strength at high temperatures. / CS-PF elyaf karışımlarındaki CS içeriğinin artması genellikle yüksek sıcaklıklarda basınç dayanımını azaltmıştır.

Aim (Amaç): To investigate the effects of waste concrete sludge and polypropylene fibers on the properties of foam concrete to promote sustainability. / Atık beton çamuru ve polipropilen liflerin köpük beton özelliklerine etkilerini araştırarak sürdürülebilirliği teşvik etmek.

Originality (Özgünlük): This study combines waste concrete sludge and polypropylene fibers to improve the physico-mechanical and thermal properties of foam concrete. / Bu çalışma, köpük betonun fiziksel, mekanik ve termal özelliklerini geliştirmek amacıyla atık beton çamuru ve polipropilen lifler bir arada kullanmaktadır.

Results (Bulgular): The use of CS reduced compressive strength but increased apparent porosity, while PF improved mechanical properties and reduced microcracking. / CS kullanımı basınç dayanımını azaltıp görünür gözenekliliği artırırken, PF katkısı mekanik özellikleri iyileştirmiş ve mikro çatlakları azaltmıştır.

Conclusion (Sonuç): The combination of CS and PF presents a sustainable alternative in foam concrete production, offering improved mechanical, physical and high-temperature resistance performance with reduced environmental impact. / CS ve PF'nin birlikte kullanımı, çevresel etkileri azaltırken mekanik, fiziksel ve yüksek sıcaklık dayanım performansını artırarak köpük beton üretiminde sürdürülebilir bir alternatif sunmaktadır.



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Abstract

Reusing construction waste conserves natural resources and reduces carbon emissions related to cement production. This study investigates the potential of using waste concrete sludge (CS) and polypropylene fiber (PF) to improve the physico-mechanical and thermal properties of foam concrete while promoting sustainability. Foam concrete is known for its lightweight and high thermal insulation properties, and in this research, CS is used as a partial replacement for cement at varying levels (10%, 20%, 30%), while PF is added 1.5% for reinforcement. The results show that as the CS content increases, the compressive and flexural strengths decrease, porosity and capillarity increase, and the density decreases. This is due to the lower binding property and higher water retention capacity of CS compared to cement. In CS10P-CS20P-CS30P samples with PF addition, porosity remained at a lower level compared to CS10-CS20-CS30 samples. This is because CS partially reduces porosity by filling some of the voids formed by the fibers. Capillarity reached its highest level in CS20P with the maximum microvoid structure formed by CS and PF fibers. While the compressive strength decreased with the increase in CS, it increased compared to the mixtures without fibers and reached its highest value in CS10P. The addition of PF provided higher compressive and flexural strength than the mixtures without CS by controlling microcracks. This research highlights that utilizing waste materials in the construction industry is a cost-effective and ecologically beneficial approach and underscores the need to expand the potential applications of such materials in the construction sector.

Atık Malzeme Kullanılarak Çevre Dostu Köpük Beton Üretimi: Atık Beton Çamuru ve Elyaf Katkılarının Etkileri

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Öz

İnşaat atıklarının yeniden kullanımı, doğal kaynakları korumaya ve çimento üretimine bağlı karbon emisyonlarını düşürmeye yardımcı olmaktadır. Bu çalışma, atık beton çamuru (CS) ve polipropilen lifin (PF) köpük betonun fiziksel-mekanik ve termal özelliklerini iyileştirme potansiyelini araştırarak sürdürülebilirliği teşvik etmeyi amaçlamaktadır. Köpük beton, hafifliği ve yüksek ısı yalıtımı özellikleri ile bilinir ve bu çalışmada, CS çimentonun kısmi ikamesi olarak farklı oranlarda (%10, %20, %30) kullanılırken, PF ise takviye amacıyla %1.5 oranında eklenmiştir. Sonuçlar, CS içeriği arttıkça basınç ve eğilme dayanımlarının azaldığını, gözenekliliğin ve kılcalığın arttığını aynı zamanda yoğunluğun da düştüğünü göstermektedir. Bu durum, CS'nin çimentoya kıyasla daha düşük bağlayıcı özelliği ve daha yüksek su tutma kapasitesinden kaynaklanmaktadır. PF katkısıyla CS10P-CS20P-CS30P numunelerinde, gözeneklilik CS10-CS20-CS30 numunelerine kıyasla daha düşük seviyede kalmıştır. Bunun nedeni, CS'nin liflerin oluşturduğu bazı boşlukları doldurarak gözenekliliği kısmen azaltmasıdır. Kılcalık ise CS ve PF fiberlerin birlikte oluşturduğu maksimum mikro boşluk yapısı ile en yüksek seviyesine CS20P'de ulaşmıştır. CS artışıyla basınç dayanımı düşerken lif kullanılmayan karışımlara göre artış göstermiş CS10P'de en yüksek değerine ulaşmıştır. PF eklenmesi, mikro çatlakları kontrol ederek CS içermeyen karışımlara kıyasla daha yüksek basınç ve eğilme dayanımı sağlamıştır. Bu araştırma, atık malzemelerin inşaat sektöründe kullanılmasının maliyet etkin ve ekolojik açıdan faydalı bir yaklaşım olduğunu vurgulamakta ve bu tür malzemelerin inşaat sektöründeki potansiyel uygulamalarını genişletme gereksinimini öne çıkarmaktadır.

1. INTRODUCTION (GİRİŞ)

Energy efficiency in buildings, particularly concerning heating requirements, is a critical area in sustainable construction [1-3]. Heating constitutes a significant portion of energy consumption in residential and commercial structures, often contributing to high levels of carbon emissions due to reliance on non-renewable energy sources like fossil fuels [4-6]. In regions with colder climates, buildings are responsible for a large share of national energy demand, driving the need for more efficient insulation materials and technologies that reduce heat loss [7-9]. The primary goal of energy-efficient design in buildings is to minimize energy use while maintaining comfortable indoor conditions [10,11]. Achieving this can result in a reduction in both operational costs and the environmental footprint, particularly in terms of CO₂ emissions, which are major contributors to climate change [12,13]. Incorporating waste materials into construction products has gained attention as a sustainable approach to reduce both construction costs and environmental impact [14,15]. Reusing industrial and construction waste, such as recycled concrete, slag, and fly ash, helps decrease the need for virgin raw materials while reducing the environmental burdens of waste disposal [16,17]. This practice is aligned with circular economy principles, where materials are kept in use for as long as possible [18,19]. Waste materials in construction not only contribute to resource efficiency but also enhance certain properties of building materials, such as durability and thermal insulation [20].

Waste concrete sludge (CS), a byproduct of the concrete manufacturing process, poses disposal challenges [21]. Worldwide, millions of tons of concrete sludge are produced annually from concrete production and cleaning processes [22]. This waste material is typically composed of water, cement, and fine particles, making it a potential resource for sustainable construction materials [14]. When processed properly, waste concrete sludge can be incorporated into new concrete mixes, reducing the need for virgin cement and mitigating landfill waste [23]. By utilizing CS as a partial substitute for cement in foam concrete, significant improvements in sustainability can be achieved while minimizing the environmental impact of concrete waste [24]. Foam concrete is a lightweight material that offers high thermal insulation properties, making it an ideal choice for energy-efficient building applications [25]. The introduction of fibers, such as polypropylene, into foam concrete mixtures enhances both mechanical

and thermal performance [26]. Fibers increase the material's flexural strength, reduce cracking, and improve durability under stress [27]. Additionally, fiber-reinforced foam concrete exhibits better resistance to high temperatures, as the fibers help prevent crack propagation and structural degradation at elevated temperatures [28,29]. These advantages make foam concrete with fiber additives a versatile and sustainable material for modern construction needs [30].

This study evaluates the physico-mechanical and thermal performances of foam concretes produced using waste concrete sludge (CS) and polypropylene fiber (PF). PF was preferred due to its advantages, such as preventing early-age crack formation, improving mechanical strength, and regulating water absorption rates. The study aims to investigate the effects of substituting CS in specific proportions for cement and PF addition on foam concrete's strength, water absorption, and high-temperature behavior. In particular, how CS contributes to material performance and how critical properties of the material, such as mass loss and compressive strength, change at high temperatures are analyzed. In this context, the structural properties of mixtures containing CS and PF are examined in detail, and new approaches are aimed to be presented in sustainable construction material production. This study is one of the rare studies that aims to contribute to the production of sustainable building materials by evaluating industrial waste such as waste concrete sludge. In particular, using CS as an alternative binder material in foam concrete production offers an environmentally friendly solution while reducing material costs.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

This study used CEM II A/LL 42.5R cement conforming to TS EN 197-1 standard to produce foam concretes. The specific gravity of the cement is 3.13, and the specific surface area (according to the Blaine method) is 3300 cm²/g. Up to 30% of the waste concrete sludge (CS) was used instead of cement to produce foam concrete. CS was obtained from the sedimentation tank of a ready-mixed concrete company in Kastamonu province. After the CS was removed from the sedimentation tank, it was dried in the open air for three days and then dried in an oven at 105 °C for 24 hours to lose the water in its structure. The specific gravity of CS is 2.84, and all of its particles are below 75 µm. The chemical characterization of cement and CS is given in Table 1.

Table 1. Chemical composition of CEM II A/LL 42.5R and CS (CEM II A/LL 42.5R ve CS'nin kimyasal bileşimi)

Oxide (by weight %)	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	MgO	SO ₃	LOI
Cement	61.8	21.3	5.2	2.4	0.2	0.9	2.5	3.1	2.1
CS	43.3	20.4	4.7	2.8	1.1	0.6	1.9	1.4	23.3

Table 2. Technical specifications of the PF (PF'nin teknik özellikleri)

Properties	Values
Length (mm)	6
Diameter (µm)	18
Tensile strength (MPa)	400
Specific gravity	0.91
Young's modulus (MPa)	9000
Elongation (%)	15
Fusion Point (°C)	176
Burning Point (°C)	595

Pumice aggregate from the Nevşehir region was used to prepare foam concretes. The specific gravity of the pumice aggregate with 0-4 mm sieve opening is 1.78, and the 24-hour water absorption is 15.2%. The particle size distribution of pumice aggregate according to ASTM C33 standard is given in Figure 1. Foam was used to prepare foam concretes to reduce unit weight and improve thermal performance. An organic resin-based admixture was used to obtain foam. Foam was obtained by mixing the foaming agent at 5% of the water weight with a high-speed mixer. The density of the formed foam is approximately 150 g/l. Polypropylene fiber (PF) of 6 mm length was also used to produce foam

concretes. Technical specifications of PF are presented in Table 2.

The cement dosage used in foam concrete production is 500 kg/m³. The water/binder (Cement + CS) ratio of all mixtures is 0.35. The w/c ratio was kept constant to clearly observe the effect of the CS ratio on the mechanical and physical properties of the concrete. In addition, 80 kg/m³ foam was used in all mixtures. CS was used instead of cement at 10, 20 and 30 % (by mass). PF was also added to the mixtures at 1.5% by volume. The mixtures produced within the scope of this study are given in Table 3.

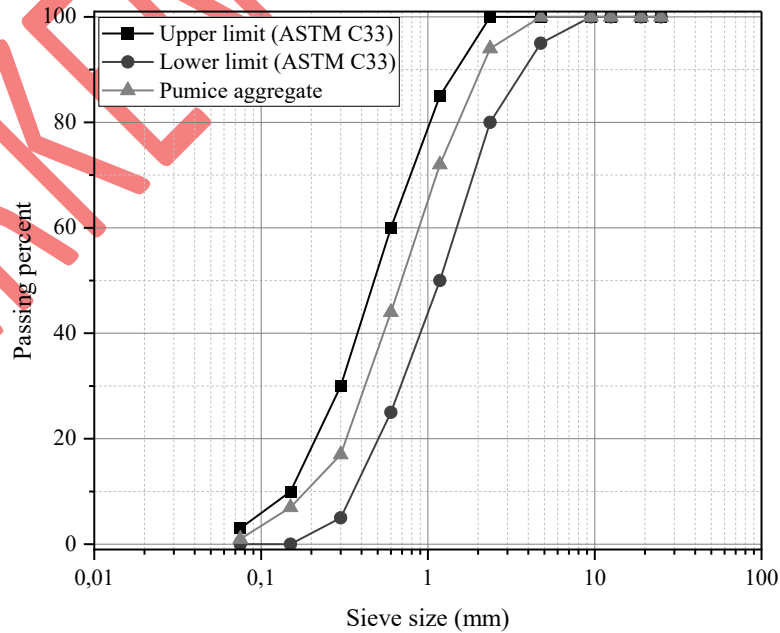
**Figure 1.** Particle size distribution of pumice aggregate (pomza agregasının tane boyutu dağılımı)

Table 3. Mixing ratios and material quantities (Karışım oranları ve malzeme miktarları)

Mixing ratio			Material quantities (kg/m ³)					
Mix ID	CS (%)	PF (%)	Cement	CS	Water	Foam	Pumice	PF
CS0	0	0	500.0	0.0	175.0	80.0	236.3	0.0
CS10	10	0	450.0	50.0	175.0	80.0	229.8	0.0
CS20	20	0	400.0	100.0	175.0	80.0	223.2	0.0
CS30	30	0	350.0	150.0	175.0	80.0	216.6	0.0
CS0P	0	1.5	500.0	0.0	175.0	80.0	209.6	13.7
CS10P	10	1.5	450.0	50.0	175.0	80.0	203.1	13.7
CS20P	20	1.5	400.0	100.0	175.0	80.0	196.5	13.7
CS30P	30	1.5	350.0	150.0	175.0	80.0	189.9	13.7

Foam concretes were produced with a laboratory-type Hobart mixer. Firstly, cement and CS were mixed at low speed for 1 minute. Then, water was added to the mixture, and the paste was prepared. Pumice aggregate was added to the paste and mixed at low speed for 1 minute and high speed for 2 minutes. Afterwards, foam was added to the mortar mixture and mixed at low speed for 1 minute and high speed for 1 minute. In the last step, PF was added to the mixture and mixed at high speed for two more minutes. The surface of the foam concretes placed in the molds was covered with stretch film. After 24 hours, the specimens were removed from the molds and subjected to water curing until the test day.

The physical properties of the samples were measured on day 28 following the ASTM C642 standard. For these physical properties, including apparent porosity, water absorption, and oven-dry density, 50x50x50 mm cube specimens, three for each mix, were produced. Capillary water absorption was also determined on the cube samples according to TS EN 1015-18 standard. These samples were dried in an oven at 50 °C for three days, and then a capillarity test was carried out. For the mechanical properties of the specimens, 40x40x160 mm prism specimens, three for each mix, were produced, and the flexural and compressive strengths of these specimens were determined on the 7th and 28th day. Firstly, flexural strength was determined according to the ASTM C348 standard, and then compressive strength was determined on the same specimen according to the ASTM C349 standard.

40x40x160 mm cube specimens, six for each mix, were produced to determine the high-temperature resistance of foam concrete specimens at 300, 600, and 900 °C. Weight loss and compressive strength were determined on these specimens. A muffle furnace with a heating rate of 5 °C /min was used to determine the high-temperature resistance. The

samples were kept at the target temperature for 120 minutes, removed from the furnace, and cooled in the outdoor air. The specimens were exposed to high temperatures after 28 days of water curing.

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

3.1 Fresh Characteristics (Taze Özellikler)

Figure 2 shows the spreading diameters of foam concrete containing CS. It is the mix with the highest workability with a flow diameter of 113 mm. This indicates that the foam concrete is partially fluid thanks to the optimum mixing of cement and water. It is observed that the flow diameter decreases significantly as the CS ratio increases. CS10, CS20, and CS30 mixes have flow diameters of 88 mm, 81, mm and 77 mm, respectively. This indicates that CS increases the viscosity of the mix and reduces workability. In particular, a 32% decrease is observed between CS30 and the reference mix (CS0). This is related to the fact that CS increases the water demand, and the concrete becomes stiffer. In the mixtures to which polypropylene fibers are added (CS0P, CS10P, CS20P, CS30P), it is observed that the flow diameters decrease even more.

The fibers disrupt the mixture's homogeneity and reduce the concrete's fluidity. For example, while the flow diameter in CS0P decreased to 78 mm, the flow diameter in CS30P mixture decreased to 53 mm. This is a 53% decrease compared to the reference mixture CS0. This situation is explained by fiber addition increasing CS's water retention capacity. When changing from CS0 to CS10 mix, workability decreased by 22%. In the CS0P mix, workability decreased by 31% to 78 mm compared to the reference mix despite the addition of fibers. CS30P mix had the most minor flow diameter and showed a 53% loss of workability compared to CS0.

The adverse effects of CS on workability are observed in the study. While increasing the proportions of CS increases the consistency of the mixture, adding polypropylene fibers further

reduces the flow diameter. This reveals that fiber-added CS mixtures should be designed with a careful water/cement ratio regarding workability.

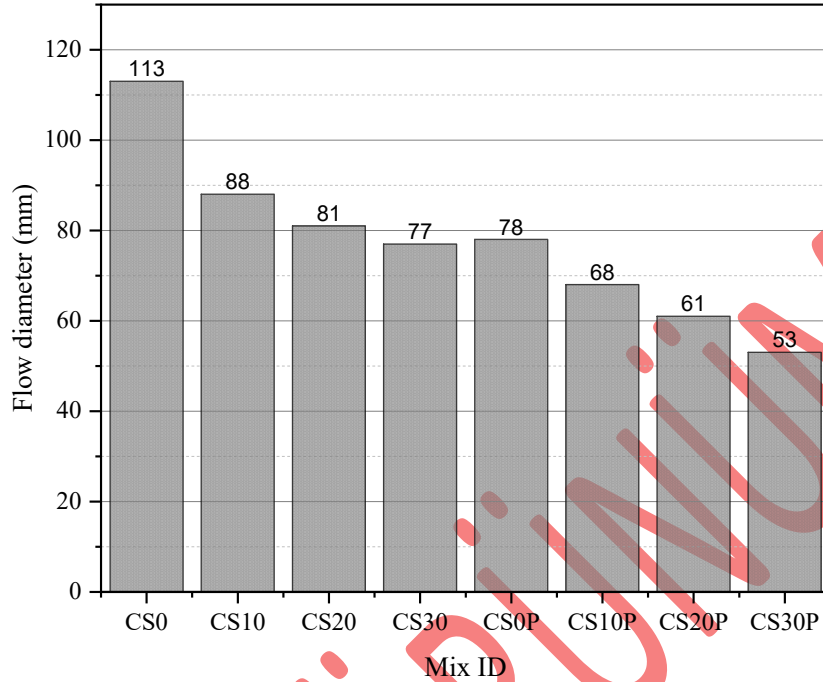


Figure 2. Fresh state characteristics of CS-containing foam concretes (CS içeren köpük betonların taze özellikleri)

3.2 Physical Characteristics (Fiziksel Özellikler)

Figure 3a shows the apparent porosity (%) and oven-dry density (kg/m^3) values of foam concrete mixes with different CS (concrete sludge) contents. The graph clearly shows how these two physical properties are affected by increasing CS content. The porosity of CS0, the reference mix without CS, is the lowest. Porosity increases as the CS content rises to 10%, 20% and 30%. Especially at CS30, the highest porosity value is reached. This can be explained by the fine structure of CS and the high loss-on ignition value (LOI 23.3%), which gives more porosity to the structure. Porosity is slightly lower in mixtures containing CS and fibers. It is possible to say that fibers reduce porosity by partially filling the voids in the microstructure.

The reference mixture without CS has the highest density. The density decreases as the CS content increases by 10%, 20%, and 30%. This decrease is due to the lower specific gravity of CS (2.84) compared to cement (3.13). In addition, CS absorbs more water, and the porosity increases, leading to a decrease in density. In mixtures with added fibers (e.g., CS0P), the density is lower than in reference mixtures due to the low specific gravity of the fibers (0.91).

When CS is used as an alternative to cement in the mix, it increases porosity and decreases density. Due to its high LOI value, CS introduces more pores into the structure, which is the main reason for this result. On the other hand, in CS mixtures containing fiber additives (CS10P-CS20P-CS30P), although the porosity increased with the increase in CS, it remained at a lower level compared to CS mixtures without fibers. This is because CS partially reduces porosity by filling some of the voids created by the fibers. Fibers act as an additive in the mix, increasing the tensile strength but decreasing the density. These results show that there are significant physical changes that can affect both the mechanical and thermal performance of the material. Porosity and density are critical parameters for thermal insulation and the strength of foam concrete.

Figure 3b shows the immersion water absorption (%) and capillary water absorption (kg/m^2) properties of foam concrete mixes with different CS and polypropylene fiber contents. These graphs reveal the relationship between the content of the mix and the water absorption capacity.

The reference mix without CS has the lowest immersion water absorption value. This is due to its low porosity and denser structure. The immersion water absorption rate increases as the CS content increases to 10%, 20%, and 30%. The highest

immersion water absorption value is observed in the CS30 mixture. The main reason is that CS creates a more porous structure and contributes to water absorption. The water absorption rate increases in mixtures containing fibers (e.g., CS0P) compared to the reference mixture. The water absorption capacity increases due to the effect of the fibers on the pore structure. In addition, the relative reduction of the workability of the fibers is effective in this process.

The reference mix again has the lowest capillary water absorption value. This is due to its low porosity and dense structure restricting the capillary transport of water. As the CS ratio increases, capillary water absorption rises significantly. The highest capillary water absorption is mainly observed in the CS30 mixture. The increase in the porous structure causes faster and more water absorption. In CS mixtures containing PF fiber additives (CS10P-CS20P-CS30P), capillary water generally increased and reached its highest level in CS20P. Because CS increases the water retention

capacity, it causes more water absorption. However, the highest capillary water absorption was observed in CS20P; the micro-void structure formed by CS and PF fibers reached the maximum level, and capillary water absorption reached the highest level. For example, the capillary water absorption of the CS20P mixture increased by approximately 40% compared to the reference mixture (CS0). However, in CS30P, capillary water decreased again because excessive porosity partially balanced the water flow.

As the CS content increased and polypropylene fibers were used, significant increases occurred in immersion and capillary water absorption rates. CS increased the water absorption by imparting more porosity to the mixture, while polypropylene fibers enhanced this situation with their effect on the pore structure. This increase in water absorption properties is considered an essential parameter in terms of the durability and long-term performance of the mixtures.

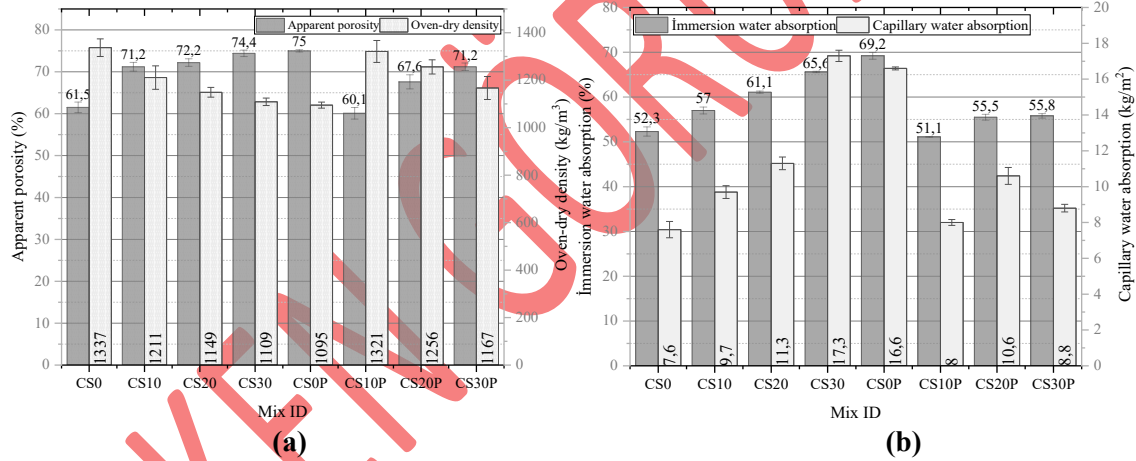


Figure 3. Physical characteristics of CS-containing foam concretes: (a) Apparent porosity and oven dry density, (b) Immersion and capillary water absorption (CS içeren köpük betonların fiziksel özellikleri: (a) Görünür porozite ve fırında kurutulmuş yoğunluk, (b) Daldırma ve kapiler su emme oranı)

3.3 Mechanical Characteristics (Mekanik Özellikler)

Figure 4a shows foam concrete mixes' 7-day and 28-day compressive strength (MPa) values with different CS content and polypropylene fiber admixture. This graph allows us to understand the effect of increasing CS content and fiber reinforcement on mechanical strength. The reference mix without CS (CS0) has the highest compressive strength. This is expected due to the high cement content and low porosity. The compressive strength decreases as the CS content increases to 10%, 20% and 30%. The compressive strength decreases significantly, especially in the

mixture containing 30% CS. This is due to the lower binding properties of CS compared to cement. The fiber additive has a slight positive effect on the 7-day compressive strength. Some increase in strength is observed mainly in the CS0P mix. Fibers can increase the strength by restricting crack propagation at early ages. The CS30P mix has an approximately 13% lower compressive strength than the reference mix CS0. This shows a significant decrease in strength by increasing the amount of CS to 30% and adding fiber.

As the amount of CS increases, 28-day compressive strength also decreases. The loss of strength is

especially evident in the mixture containing 30% CS. Since the binding properties of CS are lower than those of cement, mechanical strength is reduced in the long term. A slight improvement in the compressive strength of mixtures with added fibers (e.g., CS10P and CS20P) was observed compared to mixtures with CS. Fibers can increase compressive strength by preventing the propagation of microcracks, especially at late ages. The CS30 mix shows a 28-day strength, approximately 42% lower than the reference mix. This indicates that CS weakens the mechanical properties of the mix in the long term.

In CS mixtures containing PF fiber additive (CS10P-CS20P-CS30P), compressive strength decreased with increasing CS but increased compared to mixtures without fiber. As the amount of CS increases, the compressive strength generally reduces due to the decrease in binding. However, by controlling microcracks, adding fibers provided higher compressive strength. CS has lower binding properties than cement, and the increase in pore structure adversely affects the mechanical strength. Although polypropylene fibers partially prevent strength loss by slowing down the progression of cracks, this effect is limited in mixtures with high CS content.

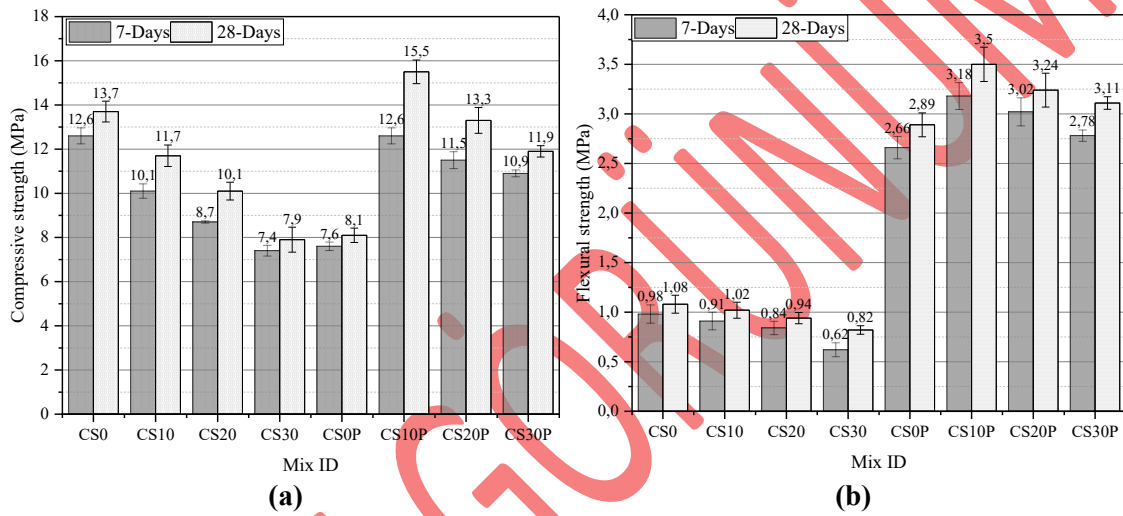


Figure 4. Mechanical characteristics of CS-containing foam concretes: (a) Compressive strength, (b) Flexural strength (CS içeren köpük betonların mekanik özellikleri: (a) Basınç dayanımı, (b) Eğilme dayanımı)

Figure 4b shows the 7 and 28-day flexural strength (MPa) results of foam concrete mixtures with different CS and polypropylene fiber contents. Flexural strength is an important parameter that reveals the material's resistance against crack formation and propagation.

The reference mix without CS has the highest flexural strength at seven days. This is entirely due to the cement-based mix's more robust binder structure and lower porosity. The flexural strength decreases significantly as the CS content increases to 10%, 20% and 30%. There is a severe decrease in flexural strength, especially in the mixture containing 30% CS. CS is a weaker material than cement's mechanical binding strength, negatively affecting the crack strength. The fiber additive positively affects flexural strength, especially at early ages. The strength of the CS0P mix is higher than the reference mix without fibers. Fibers can improve flexural strength at early ages by limiting crack propagation. The CS30 mix has a flexural strength approximately 40% lower than the

reference mix CS0. This indicates a significant decrease in flexural strength with an increase in CS to 30%. Although the CS10P mix has a flexural strength about 225% higher than CS0, its strength has improved more than the other CS-containing mixes due to the positive effect of the fiber additive.

The reference mix also has the highest value in 28-day flexural strength. As the cement hydration continues over time, an increase in mechanical strength is observed. As the CS ratio increases, the 28-day flexural strength decreases significantly. The mixture containing 30% CS has the lowest flexural strength. Using high amounts of CS substantially reduces the material's flexural strength in the long term. Blends with added polypropylene fibers (e.g., CS0P and CS10P) also show a partial improvement in the 28-day flexural strength. The fibers improve flexural strength by preventing the formation and propagation of microcracks. The CS30P mix has a flexural strength about 187% higher than the reference mix after 28 days. The CS10P mix has a flexural strength about 224%

higher than the reference mix but still outperformed the other mixes containing CS thanks to the fiber additive. Increasing the amount of CS decreases the flexural strength both in the short and long term. In CS mixtures containing PF fiber additive (CS10P-CS20P-CS30P), while the flexural strength decreased with the increase in CS, it increased compared to the mixtures without fiber. Because CS partially reduces porosity by filling some of the voids created by the fibers. This is mainly due to the weaker mechanical binding properties of CS compared to cement, and the increase in pore structure reduces the resistance to crack propagation. Adding polypropylene fibers is particularly beneficial in terms of flexural strength and partially compensates the strength losses by preventing the formation of cracks.

3.4 High-temperature resistance (Yüksek Sıcaklık Dayanımı)

Figure 5a shows foam concrete mixtures' compressive strength (MPa) results with different CS and polypropylene fiber contents at elevated temperatures (300°C, 600°C, and 900°C). High-temperature resistance is an important parameter reflecting the ability of the material to maintain its structural integrity under extreme conditions such as fire. The CS10P shows the highest compressive strength at 300°C. This is because PF controls early-age cracks and preserves the microstructure. As the amount of CS increases, a decrease in compressive strength at 300°C is observed. Especially a significant reduction is observed in the CS30 mixture. The lower thermal strength of CS compared to cement causes the material to weaken more at high temperatures. Fiber additives increased the strength of the material at 300°C. Especially in CS10P, CS20P and CS30P mixtures, improvement in compressive strength is observed with the addition of fibers. Fibers can increase the strength by limiting microcracks and balancing thermal expansions. The CS30 mix showed a strength approximately 35% lower than the reference mix CS0. This is a result of the lower thermal stability of CS compared to cement. The CS10P mix exhibited a strength of about 5% higher than the reference mix.

At 600°C, a significant decrease in the strength of the reference mix is observed, but it still outperforms the other mixes—damage to the cement matrix at high-temperature results in loss of strength. The decrease in compressive strength at 600°C is more pronounced as the CS content

increases. Especially the mixture containing 30% CS experienced a severe loss of strength. CS becomes more porous at high temperatures, weakening its mechanical strength. The presence of fibers improved the strength at 600°C. Fibers can help the blend to perform better at high temperatures. This is mainly due to the melting of PF, which reduces capillary voids. The CS30 mix exhibited a compressive strength 38% lower than the reference mix. The CS10P mix exhibited a strength approximately 9% higher than the reference mix.

At 900°C, the strength of the reference mix is considerably lower. At this temperature, damage to the microstructure of the cement leads to a severe reduction in strength. The compressive strength at 900°C drops dramatically as the CS content increases. The CS30 mix experiences an almost complete loss of strength. The inability of CS to maintain its structural integrity at high temperatures is the main reason for this loss. At 900°C, the effect of the fibers is more limited, although they still have a strength-improving impact in some mixtures. The CS10P mix showed a strength of approximately 10% higher than the reference mix. The effect of CS and fibers on the strength at this temperature is noteworthy.

The negative effect of high temperatures on compressive strength becomes more pronounced as the CS content increases. CS exhibits a weaker resistance to high temperatures compared to cement. Polypropylene fibers have a strength-enhancing effect (due to melting), especially at lower temperatures such as 300°C and 600°C, but this effect is limited at very high temperatures such as 900°C. The importance of fiber additives in maintaining the material's structural integrity under extreme temperature conditions such as fire. In CS mixtures containing PF fiber additives at 300°C, 600°C, and 900°C (CS10P-CS20P-CS30P), compressive strength decreased with increasing CS but increased compared to mixtures without fiber. In CS mixtures with PF fiber additives (CS10P, CS20P, CS30P), higher strength was preserved compared to samples without CS due to the control of early age cracks and protection of microstructure by PF fibers. Based on this, PF fibers cause strength loss at high temperatures in CS0P because the voids formed by the melting of the fibers reduce the strength. However, in CS10P, PF fibers provide early age crack control, delaying the strength loss at high temperatures and providing higher strength than CS-added concretes without PF.

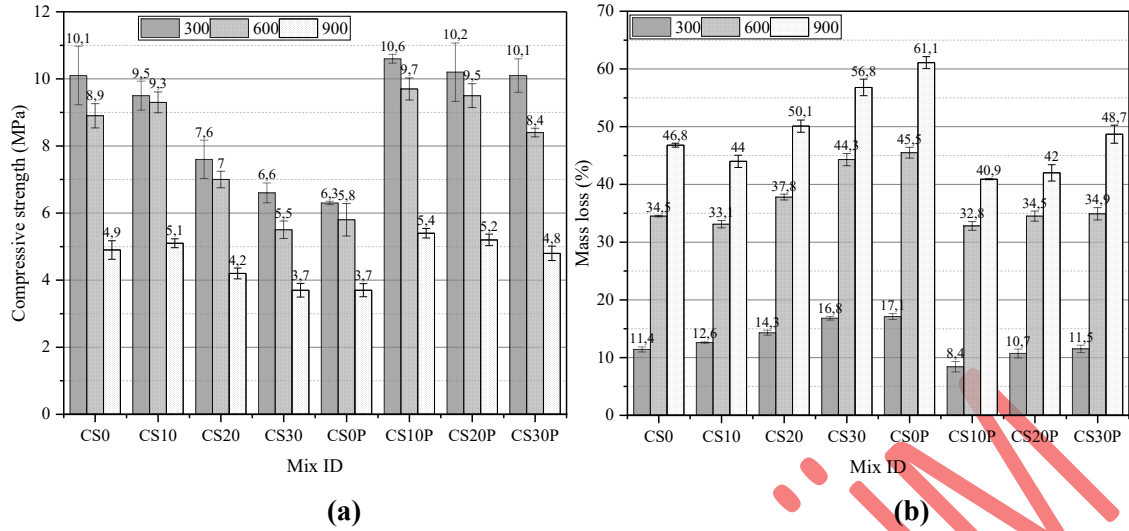


Figure 5. High-temperature resistance of CS-containing foam concretes: (a) Compressive strength, (b) Mass loss (CS köpük betonların yüksek sıcaklık dayanımı: (a) Basınç dayanımı, (b) Kütle kaybı)



Figure 6. Foam concretes containing CS exposed to 900°C (900°C'ye maruz kalan CS içeren köpük betonlar)

Figure 5b shows the mass loss (%) of foam concrete mixtures with different CS and polypropylene fiber contents at elevated temperatures (300°C, 600°C, and 900°C). Mass loss is another critical parameter that helps to evaluate the thermal strength and structural stability of the material exposed to high temperatures.

The CS10P has the lowest mass loss at 300°C. Mass loss increases as the CS ratio rises. Higher mass loss is observed in the mixture containing 30% CS. Since CS has a high water retention capacity, water loss increases at temperatures up to 300°C, causing mass loss. The fiber additive reduced the mass loss at 300°C. The fibers maintained the thermal microstructure at this temperature. Especially CS0P and CS30 mixtures lost more mass at this temperature. The CS30 blend lost approximately 47% more mass than the reference blend CS0. This difference is due to the water retention capacity and

low thermal stability of CS. The CS0P blend lost approximately 50% more mass than the reference blend. Polypropylene fibers experience thermal degradation at this temperature, causing additional mass loss.

At 600°C, the mass loss of the reference mixture increases significantly compared to 300°C but remains lower than the mixtures containing CS. At this temperature, significant damage begins to occur in the cement matrix. As the CS content increases, the mass loss also increases. A serious mass loss is observed, especially in the mixture containing 30% CS. This is related to the higher degradation of CS at higher temperatures due to its high LOI. The addition of fibers further slightly decreases the mass loss at 600°C.

At 900°C, a significant mass loss occurs in the reference mixture. At this temperature, the cement

structure is severely damaged. As the CS content increases, the mass loss at 900°C increases dramatically. In particular, the CS30 mixture experiences a mass loss of almost 56.8% at this temperature. This indicates that CS has low thermal stability and rapidly loses its structural integrity at high temperatures. The fiber addition continues to increase the mass loss at 900°C. In particular, fiber mixtures exhibit serious thermal deterioration at this temperature, causing the material to lose mass. The CS30P blend experienced more than 4% mass loss compared to the reference blend at 900°C. CS and fibers damage the material structure at this temperature and accelerate mass loss. At high temperatures, the increase in CS content significantly increases the mass loss. Especially at extreme temperatures such as 600°C and 900°C, structural integrity is rapidly lost due to the low thermal stability of CS. In CS mixtures containing PF fiber additives (CS10P-CS20P-CS30P), mass loss increased with the increase in CS but decreased compared to mixtures without fiber. In CS mixtures with PF fiber additives (CS10P, CS20P, CS30P), less mass loss occurred compared to samples without CS due to the control of early age cracks and protection of microstructure by PF fibers. In extreme conditions such as fire, it may be necessary to limit the CS content and review the use of fibers to minimize the mass loss of the material.

The surface properties of foam concrete containing CS exposed to 900 °C are given in Figure 6. While no damage was observed on the surface of the foam concretes after 300 and 600 °C, map cracks formed on the surface after 900 °C. Despite this, foam concrete maintains its structural integrity.

4.CONCLUSIONS (SONUÇLAR)

It is revealed that CS and PF additives reduce workability in foam concrete production. Still, this effect can be minimized with appropriate water/cement ratios and additive arrangements in material design. It has been concluded that appropriate water additives or chemical additives should be used to improve workability, especially by balancing the water requirement of CS.

Waste concrete sludge (CS), used in certain proportions instead of cement, directly affected the physical-mechanical properties of foam concrete. As the CS content increased, the compressive and flexural strength of the material decreased both at early ages and in the long term. This decrease is due to the weaker binding properties of CS compared to cement. Including CS in the mixture increased the apparent porosity of the material and reduced its

density. This caused the foam concrete to become lighter but less durable.

Adding polypropylene fibers provided improvement, especially in flexural strength, and helped the material resist crack propagation. The fiber addition increased strength by regulating the pore structure and water absorption rates. The effect of PF addition on compressive strength was more pronounced in mixtures containing low amounts of CS. The potential of fibers to stabilize the material at high temperatures was observed, but it was found that this effect was limited at very high temperatures.

In CS mixtures containing PF additive (CS10P-CS20P-CS30P), compressive strength decreased with increasing CS but increased compared to mixtures without fiber. As the amount of CS increases, the compressive strength generally reduces due to the decrease in binding. However, by controlling microcracks, adding PF provided higher compressive strength than mixtures without CS. On the other hand, this mixtures, while the flexural strength decreased with the increase in CS, it increased compared to the mixtures without fiber. This is because CS partially reduces porosity by filling some of the voids created by the fibers.

Although porosity increased with the increase in CS mixtures with PF additives (CS10P-CS20P-CS30P), it remained lower than CS mixtures without PF. This is because CS partially reduces porosity by filling some of the voids formed by the fibers. On the other hand, although water absorption increased with the increase in CS. This mixture remained at a lower level than CS mixtures without PF.

Capillary water absorption generally increased in CS mixtures containing PF additives (CS10P-CS20P-CS30P) and reached its highest level in CS20P. CS increased the water retention capacity and caused more water to be absorbed. However, the highest capillary water absorption was observed in CS20P. In CS20P, the microvoid structure formed by CS and PF reached the maximum level, and capillary water absorption reached the highest level. However, in CS30P, capillary water absorption decreased again because the excessive porosity partially compensated for water permeation.

Foam concrete containing CS and PF exhibited partial durability at temperatures up to 300°C and 600°C; however, when the temperature increased to 900°C, especially in mixtures containing high CS content, there were severe decreases in compressive strength and mass losses. Mass loss at 900°C

increased significantly as the CS content increased. This is due to the lower thermal stability of CS compared to cement.

In CS mixtures containing PF fiber additives (CS10P-CS20P-CS30P), compressive strength decreased with increasing CS, which increased compared to mixtures without fiber. This mixtures higher strength was preserved compared to samples without CS due to PF fibers controlling early age cracks and protecting the microstructure. However, while mass loss increased with increasing CS, it decreased compared to mixtures without fiber. This mixtures, less mass loss was experienced compared to samples without CS due to PF fibers controlling early age cracks and protecting the microstructure.

This study demonstrated the usability of waste concrete sludge in producing sustainable building materials, and it was shown that polypropylene fiber additives could positively affect mechanical and thermal strength. However, since using CS at high rates may negatively affect foam concrete's durability and long-term performance, it should be carefully evaluated in material design. Although fiber additives have a role in enhancing material performance at high temperatures, it was observed that they should be optimized especially for extreme conditions such as fire situations.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Yazarlar çalışmaya eşit oranda katkı sağlamıştır.

The authors have contributed equally to the work.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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