JOURNAL OF
JCIVILTECH
INNOVATIONS IN CIVIL ENGINNERING AND TECHNOLOGY

e-ISSN 2687-2129
jciviltech, ***2023***, *5(2), 71-90*

Araştırma Makalesi / Research Article

Effect of Denim Waste Fibres on Technical Properties of Cementitious Lightweight Composite Mortars

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Geliş / Recieved: 27.05.2023; Kabul / Accepted: 28.12.2023

Abstract

The aim of this study was to investigate the utilization of recycled denim waste fibers (DWF) for reinforcing cementitious lightweight composite mortar (CLCM). The research focused on evaluating how the addition of DWF affected various aspects of CLCMs, such as flowability, fresh and hardened unit weight, porosity, water absorption, flexural strength, compressive strength, and load-deformation characteristics. Different proportions of fibers (0, 0.25, 0.50, 0.75, 1.00, 1.25, and 1.50 wt.% of cement) were incorporated into the CLCM. The results showed a slight decrease in both fresh and hardened unit weights compared to the reference. It was noted that the consistency of the mortars declined with the increasing addition of fibers. Additionally, the inclusion of any amount of fiber led to an enhancement in the mechanical properties of the lightweight mortars. Furthermore, the reference mortar exhibited less deformation under load, indicating its higher brittleness. Moreover, the study observed that the incorporation of DWFs had the ability to simultaneously improve both the ultimate load-bearing capacity and deformation of the mortars.

Keywords: *Denim waste fibre, Fibre reinforcement, Lightweight composite mortar, Load-deformation, Strength*

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Bu makaleye atıf yapmak için
Kalkan, Ş. O., Öcal, H. İ. & Gündüz, L. (2023). Effect of Denim Waste Fibres on Technical Properties of Cementitious Lightweight Composite Mortars. *Journal of Innovations in Civil Engineering and Technology (JCIVILTECH), 5(2)*, 71-90.

Kot Atık Liflerinin Çimento Esaslı Hafif Kompozit Harçların Teknik Özelliklerine Etkisi

Öz

Bu çalışmanın amacı geri dönüştürülmüş kot atık liflerinin (KAL), çimento esaslı hafif kompozit harç (ÇHKH) takviyesi için kullanımını incelemektir. Bu araştırma, KAL eklemesinin, kıvam, taze ve sertleşmiş birim ağırlık, gözeneklilik, su emme, eğilme dayanımı, basınç dayanımı ve yük-deformasyon gibi ÇHKH'lerin çeşitli özelliklerini nasıl etkilediğini değerlendirmeye odaklanmaktadır. Farklı lif oranları (çimentonun ağırlıkça %0, %0.25, %0.50, %0.75, %1.00, %1.25 ve %1.50) ÇHKH'lara ilave edilerek kullanılmıştır. Test sonuçları, referans numunesine kıyasla hem taze hem de sertleşmiş birim ağırlıklarda hafif bir azalma olduğunu göstermiştir. Harçların kıvamının lif eklemesi arttıkça azaldığı gözlemlenmiştir. Ayrıca, çalışma kapsamında kullanılan bütün lif dozajlarının eklenmesinin hafif harçların mekanik özelliklerini artırdığı görülmüştür. Bu sonuçlara ilave olarak, referans harcı yük altında daha az deformasyon sergilemiş, bu da daha referans harcı için yüksek kırılganlığına işaret etmiştir. Ayrıca, bu çalışmada KAL'lerin harçların hem nihai yük taşıma kapasitesini hem de deformasyonunu aynı anda artırma yeteneğine sahip olduğunu tespit edilmiştir.

Anahtar kelimeler: *Kot atık lifi, Lif takviye, Hafif kompozit harç, Yük-deformasyon, Dayanım*

1. Introduction

The construction sector is a prominent consumer of materials, and it is crucial to utilize more efficient raw materials in the production of construction materials. Recycling and reusing materials are effective strategies for sustainability. Textile waste fibre is one such material. Globally, textile production exceeds 88.5 million tons annually, resulting in a significant amount of waste from the textile industry and discarded textile products. In Europe alone, the textile industry generates approximately 12 million tons of waste each year. Some of this waste is recycled into yarn, but small-sized fibres are produced as waste byproducts during this process. Unfortunately, these textile waste fibres or cuttings are either burned or end up in landfills, causing environmental harm as they are non-biodegradable (Reis, 2009; Ryu et al., 2007). However, this substantial accumulation of textile waste fibre presents an opportunity for its utilization in construction materials. The textile and garment industry are the major driving force in Turkey's thriving economy. Turkey ranks third among European countries in textile exports and is the sixth-largest garment exporter globally. With such significant production capacity, waste and residual materials generated by the textile sector vary depending on production activities. While some of these materials are recycled internally within the industry, the accumulation of waste fibre resulting from the recycling process should not be underestimated. The use of waste materials in the construction industry has gained importance in recent years, particularly due to their advantages such as thermal conductivity, sound insulation, structural reinforcement, and lightweight composite production when used in cementitious materials. Textile waste fibre is one of these valuable waste materials. Therefore, it is essential to further explore the utilization of these materials in cementitious composites from both economic and sustainable perspectives.

The utilization of fibres in concrete commenced in the early 1960s in developed nations, and since then, the applications of fibre-reinforced concrete have increased (Aghaee & Foroughi 2013). The literature reveals that various types of fibres have been employed as reinforcement elements in cementitious composites. Numerous studies have explored the benefits of different fibres, including steel fibres (Grabois et al., 2016; Pogorelov & Semenyak, 2016), polypropylene fibres (Yin et al., 2016; H. Zhang et al., 2016), glass fibres (Marikunte et al., 1997; Shah et al., 1988), and organic fibres such as sisal (Savastano Jr et al., 2003, Savastano Jr et al., 2006), coconut and oil palm (Lertwattanaruk & Suntijitto, 2015), banana (Mostafa & Uddin, 2016), and more. While research on textile-reinforced cementitious composites is often conducted to enhance masonry walls and concrete structures (Elsanadedy et al., 2013; Garmendia et al., 2014; Larrinaga et al., 2014; Papanicolaou et al., 2008; Triantafillou & Papanicolaou, 2006), there remains an insufficient investigation into the utilization of waste textile fibres in cementitious composites. In the available literature, the use of waste carpet fibres as reinforcement material is more prevalent (Aspiras & Manalo, 1995; Ucar & Wang, 2011; Wang et al., 1994) compared to other types of waste textile fibres like cotton (Binici & Aksogan, 2015; Reis, 2009), polypropylene (Murathan et al., 2014), and acrylic (Briga-Sa et al., 2013; Pinto et al., 2013).

Furthermore, there is a growing trend in the construction industry towards using lightweight aggregates to reduce dead loads and improve insulation. Lightweight aggregates can be classified into two categories: organic cellular aggregates, including expanded polystyrene foam (EPS), extruded polystyrene foam (XPS), and polyurethane foam; and inorganic cellular aggregates derived from natural and artificial sources, such as expanded perlite, expanded clay, and exfoliated vermiculite, among others (Shannag, 2011; Shoukry et al., 2016). These lightweight aggregates, such as pumice, perlite, expanded clay, vermiculite, or air entraining agents, are commonly used in the production of cementitious lightweight composite mortars (Glenn et al., 2004). Expanded clays are lightweight aggregates obtained by heating the clays in rotary kilns at around 1200°C. Expanded clays can expand up to 5-6 times their own volume as a result of outgassing when heat treated. During the heating process, the gases in the body form thousands of small bubbles, expanding the clay and forming a honeycomb structure. Expanded clays are generally round or potato-shaped as a result of the circular movement of rotary kilns and can be obtained in different sizes and different unit weights. While a hard sintered shell is formed on the outer surface, a very light, extremely durable, and porous clinker-like structure is formed on the inner side. Lightly expanded clay aggregate is used in many industrial areas. One of the most widely used fields is the production of lightweight concrete in engineering applications. It has low unit weight, water repellency, high thermal insulation, high aggregate compressive strength, good bonding ability with cement, etc. Due to their properties, their use in civil engineering applications is gaining more intensity (Gündüz et al., 2020).

Lightweight mortars are mortars that can be produced by using aggregates with lower unit weight than normal aggregates obtained through natural or artificial means, or by creating voids within the mortar using various methods. As per the specifications outlined in TS EN 998-1 (2017), a lightweight mortar must possess a hardened unit weight that is below 1300 kg/m^3. By using lightweight mortars instead of normal weight mortars in constructions, it is possible to dissipate more energy with lower dead loads. Additionally, it can contribute to thermal insulation of buildings, improving their thermal comfort properties. It can also lead to safer structures with enhanced fire resistance and provide better sound insulation in buildings, enabling the design of more comfortable structures (Coppola et al., 2018; Faghihmaleki et al., 2017; Okasha et al., 2020).

It is known that the mechanical properties of lightweight mortars are relatively low due to the lightweight aggregates and the high void content in the matrix structure. However, the physical and mechanical properties of cementitious lightweight mortars can be improved by using fibres of different origins (Kazım & Ceren, 2017; Yaprak et al., 2018; P. Zhang et al., 2019). Various types of fibres such as cellulose, polymer, synthetic, carbon, steel, etc. are used to enhance the durability properties, energy dissipation capacity, tensile strength, and toughness of the mortar (de França et al., 2016; Ji et al., 2022). The addition of fibres to cementitious mortars has long been investigated by researchers as a way to improve their mechanical properties (Abbas et al., 2019; Calis et al., 2021; Huang et al., 2022). By adding different types of fibres to mortar mixtures, improvements in compressive strength values of the mortar can be achieved, ranging from 4% to 27% (Çomak et al., 2018).

There are very limited studies on the use of very fine denim waste fibres, which are produced during the recycling of denim waste or denim production, in cementitious products. Kalkan and Gündüz (2016) determined that the use of 1.7 % denim waste fibre by weight can improve the mechanical properties of lightweight mortars. Özcan and Gündüz (2021) stated that denim waste fibres can improve the strength properties of aerated concrete. Very limited number of studies show that this waste material can have an important place in the reinforcement of lightweight mortars.

Improving the physical and mechanical properties of cementitious lightweight products, which have become increasingly important in the construction industry in recent years, has also become one of the important research topics. In this study, the effect of the amount of denim waste fibre on the properties of cement-based lightweight mortars was investigated by a series of experimental analyses. Seven different series of mortar specimens, with and without fibre additives, were created and the physical and mechanical values of these mortars were compared. The obtained data are discussed in detail, and some technical experiences that can be characterized in the context of the effects of denim waste fibre additive in R&D studies on the production of lightweight mortar in cement-based composite mortars are shared.

2. Materials and Methods

2.1 Materials

In the formulation of seven composite mortar mixes, CEM I 42.5R ordinary Portland cement (PC), which closely resembles ASTM Type I cement, was employed. The cement exhibits a specific gravity of 3.15. It is used as binder material.

Expanded clay (EC) was used as lightweight aggregate in this study. Specific gravity of EC is 2.51. The grain distribution of expanded clay was used as 0/4 mm and the sieve analysis is given in Figure 1.

The fibres used in this study have cotton and synthetic content since they are formed during the recycling of denim products produced by weaving cotton and synthetic fibres together. Average fibre diameter is 35 µm and average fibre length is 3 mm. Fibre colour is denim blue. The microscope image of the DWF is shown in Figure 2.

Regular tap water was used as mixing water.

The general view of all materials used in lightweight mortar mixes is given in Figure 3.

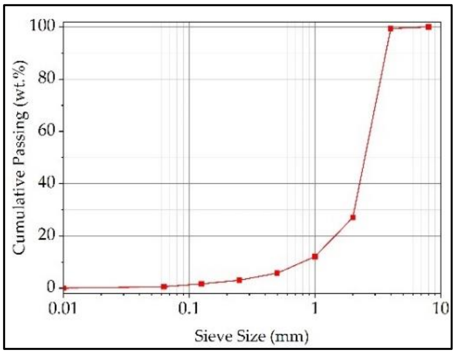

Figure 1. Sieve analysis of EC.

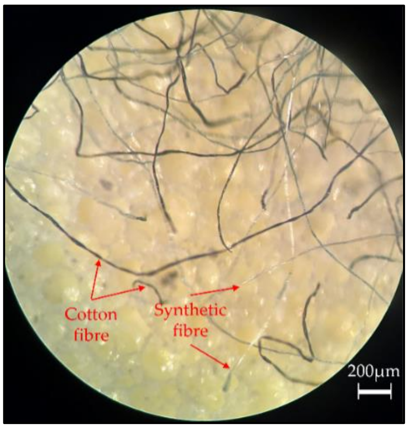

Figure 2. Microscope view of DWFs.

Figure 3. The general view of all materials used in lightweight mortar mixes.

2.2 Methods

2.2.1. CLCM production

This experimental research focused on examining the effect of denim waste fibres on physical and especially mechanical properties of cementitious lightweight composite mortars by designing various addition ratios of DWF in composite mortar mixtures. Additionally, a reference mortar mixture was formulated without the use of DWF to precisely analyse the specific effects attributable to DWF incorporation. In the study, the cement : aggregate ratio was used as 1: 2.5 and the w/c ratio was used as 0.833 at constant values. Also, DWF : cement ratio was increased from 0 to 0.25, 0.5, 0.75, 1, 1.25 and 1.5 and fibre was added to the mortar at these rates. Before the experimental part of this study began, an initial study was conducted to prepare the final mixture mix design. According to the initial test results, when the DWF:cement ratio is higher than 1.5, the flow diameter value of the composite mortar decreases significantly and the fibers become agglomerated in the mortar. Accordingly, a decrease in strength may be observed. For this reason, the highest DWF:cement ratio was used as 1.5. The composite combinations were outlined in Table 1, detailing the composition design.

Table 1. Mixture design.

Mix	PC (g)	EC (g)	DWF (g)	Water (g)	w/c	DWF/c
DWF0	900	2250	0.00	750	0.833	0.00
DWF025	900	2250	2.25	750	0.833	0.25
DWF050	900	2250	4.50	750	0.833	0.50
DWF075	900	2250	6.75	750	0.833	0.75
DWF100	900	2250	9.00	750	0.833	1.00
DWF125	900	2250	11.25	750	0.833	1.25
DWF150	900	2250	13.50	750	0.833	1.50

As can be seen from the table, PC, EC, and water are fixed in the mixtures. the only variable parameter is the amount of fibre added. As a reference mortar, DWF doesn't contain any fibre amount. Test mixtures are designed to add DWF with increasing proportions as 0.25, 0.50, 0.75, 1.00, 1.25 and 1.50 wt.% of cement. During the mixing process, the solid components were initially placed in the mixer and blended for 2 minutes to ensure a uniform dry mixture. Subsequently, water, specifically regular tap water at a temperature of 20 ± 2 ˚C, was added to the mixer to create fresh cement-based lightweight composite mortar mixtures. The mixture was then mixed for an additional 2 minutes. The prepared fresh mortar was then poured into moulds. All test specimens were retained in moulds for 24 hours at ambient temperature and subsequently demoulded. All experiments on the hardened specimens were performed following water curing at 21 ± 1 ˚C. All tests were carried out once the water-cured specimens were dried in an oven (100 ± 5 ˚C) until their weight stabilized.

2.2.2. Flowability of fresh mortars

To assess the workability characteristics of the fresh mortars, a flow table test was conducted for each individual fresh mortar specimen. The flowability of the fresh mortar specimens was evaluated using a flow table apparatus, following the guidelines outlined in ASTM C1437-15 (2013).

2.2.3. Fresh and Hardened Unit Weight

Fresh and hardened unit weight of mortars were carried out on the fresh and hardened composite specimens with respect to TS EN 1015-6 (2000) and TS EN 1015-10 (2001). The unit weight of the fresh mortars were determined immediately after their production. The unit weight values of the hardened mortars, on the other hand, were determined after the mortars were cured for 28 days.

2.2.4. Permeable porosity and water absorption

Permeable porosity of 28-days cured CLCM specimens were conducted according to ASTM C642-13 (2013) standard. Capillary water absorption test was conducted on 28-day cured 4×4×16 cm prism specimens according to the conditions specified in TS EN 1015–18 (2014) standard. The test involved exposing the broken surfaces of the specimens to water. Three pieces of specimens were produced for each series and for each test.

2.2.5. Microscopic analysis

In hardened composite mortar specimens, fracture surface photographs of the specimens were taken using a Nikon (SMZ 745T) stereo type optical microscope to observe fibre distribution, matrix structure, porosity, and aggregate-cement interface.

2.2.6. Mechanical properties

The hardened composite specimens underwent compressive and flexural tensile strength tests in accordance with ASTM C349-14 (2014) and ASTM C348-14 (2014) standards. For each test and each series, three 4x4x16 cm^3 prismatic specimens were manufactured. Mechanical tests were performed at curing periods of 7 and 28 days. The load-deformation curves of the specimens cured for 28 days were obtained during the analysis of compressive strength.

3. Results and Discussions

3.1. Flowability of fresh mortars

Figure 4 illustrates the flow indices of the composite mortar mixes represented as a percentage of the flow diameter value of the reference mix. The flow diameter of the reference batch was 200 mm, which corresponds to 100%. As the addition levels of DWF to composite mortars increased, the flow indices of the mortar specimens decreased. Thus, it is important to note that the flowability of all the mixtures was lower than that of the reference mixture. Moreover, the loss in flowability became more pronounced for addition levels of 1.25 wt.% of cement and higher. Other researchers who have studied the utilization of fibres in their research have also obtained similar results. Çankal et al. (2023) have observed that the use of glass fibres in cement mortar significantly reduces the flowability characteristic of the mortar. Similarly, in their study, Kalkan and Gündüz (2016) have determined that the use of denim waste fibres reduces the flowability characteristic of lightweight mortar containing pumice and perlite aggregates. The fibre additive has negatively affected the consistency of the mortars. This is due to the occurrence of agglomeration and interlocking of the denim waste fibres, which leads to a loss of consistency and restricts the mobility of the components in the mortar. Also, this can be attributed to the water absorption of the cotton-based fibres, as they retain water within their composition. This hampers the presence of free water in the mortar and negatively affects the fluidity of the material.

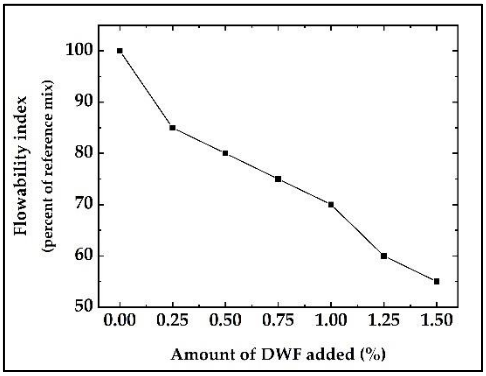

Figure 4. The flow indices of the CLCM batches.

3.2. Fresh and Hardened Unit Weight

Table 2 represents the unit weight values of fresh and hardened CLCM specimens.

Tablo 2. Fresh and hardened unit weight variations of CLCMs.

Mix	Fresh unit weight (kg/m^3)	Hardened unit weight (kg/m^3)
DWF0	1592.8	1370.5
DWF025	1578.1	1358.2
DWF050	1564.1	1348.4
DWF075	1493.7	1301.5
DWF100	1476.2	1290.4
DWF125	1451.0	1261.6
DWF150	1441.2	1259.7

A reduction in both fresh and hardened unit weight values of the CLCMs was observed when incorporating DWF at increasing levels. This decrease in unit weight can be attributed to the loss of workability in the fresh mortar when DWFs are added. As a result, more pores are retained in the mortar during the moulding process, leading to a decrease in the hardened unit weight values. Additionally, it can be said that the low unit weight of the fibres leads to a decrease in the unit weight along with the increase in the volume of the mortar. However, although there is not a significant decrease in hardened unit weight, there is a maximum unit weight loss of approximately 8%. The decrease in unit weight values of mortars with the use of fibres has been observed by other researchers as well (dos Santos Alberton et al., 2023), and this phenomenon is mostly attributed to the increased presence of air within the mortars (Ş. O. Kalkan et al., 2022).

3.3. Permeable porosity and water absorption

Table 3 represents the capillary water absorption and permeable porosity values of the hardened CLCM specimens.

Tablo 3. Capillary water absorption and permeable porosity values of the CLCM specimens.

Mix	Capillary water absorption ($kg/m^2.min^{0.5}$)	Permeable porosity (%)
DWF0	0.289	12.61
DWF025	0.345	13.78
DWF050	0.349	14.97
DWF075	0.350	15.06
DWF100	0.362	15.24
DWF125	0.364	15.31
DWF150	0.379	15.52

The primary parameter utilized in the analyses was the capillary water absorption criteria specified in the TS EN

998-1 standard for mortar derivatives. The TS EN 998-1 (2017) standard defines three distinct classes (W0-W2) for capillary water absorption (c) values in mortar groups. The specified limit values for capillary water absorption in each class are as follows: W0 class has no specified value, W1 class has a limit of c ≤ 0.40 $kg/m^2.min^{0.5}$, and W2 class has a limit of c ≤ 0.20 $kg/m^2.min^{0.5}$. Based on the test results, all specimens of the mixtures conform to the W2 capillary water absorption class as defined by the TS EN 998-1 (2017) standard. On the other hand, it has been observed that as the DWF usage rate increases, the specimens absorb more water capillary due to the increased porosity. Also, another analysis focused on the time-dependent capillary water absorption values of the cement mortar specimens, and the results are depicted in Figure 5.

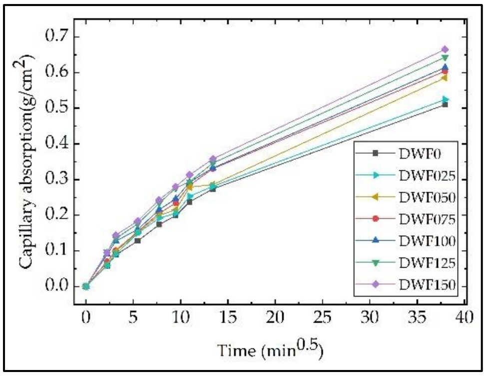

Figure 5. Capillary curves of the cement mortar specimens with DWF addition.

It has been determined that the water absorption values of the mortars increase with an increase in the usage rate of DWF in the time-dependent capillary water absorption values. This trend is found in parallel with the capillary water absorption coefficients given in Table 3. Other researchers conducting studies on the use of different natural types of fibres in cement mortar have also revealed that fibres have a property of increasing water absorption in mortars (Benaniba et al., 2020; dos Santos Alberton et al., 2023). A similar trend has been observed in the permeable porosity values, parallel to the capillary water absorption values. It was observed that the permeable porosity values of the mortars increased as the amount of DWF added to the mortar increased. In particular, a sharp increase was observed in the permeable porosity values with the addition of 0.25% and 0.50% fibre, while there was no obvious change in the porosity values at fibre utilization rates above this value. Based on this result, it can be noted that the mortar has a more compact structure with the use of 0.75% fibre and above. however, it was observed that porosity increased at all fibre utilization rates compared to the reference mortar.

3.4. Microscopic analysis

In the scope of the study, the microscopic analysis of the reference mortar specimens without DWF fibre additives, as well as the DWF reinforced CLCM test specimens, was carried out using a stereo microscope at different magnification levels to observe the general characteristics such as the matrix, aggregate, distribution of fibres, and the formation of pores. The interfacial transition zone (ITZ) between EC, DWF and cement matrix is presented in Figure 6. The overall appearances of the matrix structures for all CLCM test specimens are provided separately in Figure 7.

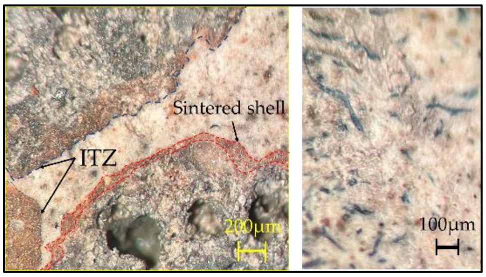

Figure 6. Interfacial transition zone of aggregate-cement matrix and DWF-cement matrix

Upon examining Figure 6, it is observed that the interface between the EC aggregate and the cement matrix appears to be compact and void-free. The cement paste demonstrates a good interlocking with the EC aggregate. Subaşı (2009) also stated that the interfacial transition zone between the cement paste and ECA (expanded clay aggregate) exhibits a strong bond. It can be anticipated that this interlocking would have a positive effect on enhancing the compressive strength. Similarly, it has been determined that the DWFs exhibit good compatibility with the cement paste. The fibre-cement interface is observed to be dense and also void-free.

Upon examining Figure 7, it is observed that the reference mortar without DWF addition exhibits a higher presence of pores in its matrix structure; however, these pores have smaller diameters compared to the test specimens. With the addition of DWF, although there is a relatively decrease in the number of pores, it is observed that the pore sizes have increased. As observed in Figure 5, Figure 6 also demonstrates the dense interface between the aggregate-cement and DWF-cement. However, especially in Figure 7(f), it can be seen that as the amount of fibre addition increases, the fibres tend to agglomerate in certain areas. The dense interface between the fibre-cement transition zone indicates that the decrease in mortar density is not due to gaps in the fibre-cement interface caused by the fibres-cement relation, but rather the result of insufficient compaction of the mortar due to decreased workability, leading to voids in the matrix structure.

3.5. Mechanical properties

Figure 8 illustrates the relationship between the flexural tensile strength of the composite mortars being studied and the level of DWF addition.

From Figure 8, it is evident that with an increase in the DWF addition level, the flexural tensile strength values of CLCMs also increase at 7 and 28 days of curing. The specimens used in the flexural strength test, which were subsequently subjected to the compressive strength test, are shown in Figure 9. When considering the duration of curing, it was noted that the flexural tensile strength of the specimens exhibited a notable increase with a prolonged water curing period. The flexural tensile strength of the reference mix (DWF0) was measured at 2.15 MPa and 2.53 MPa after 7 and 28 days of curing, respectively.

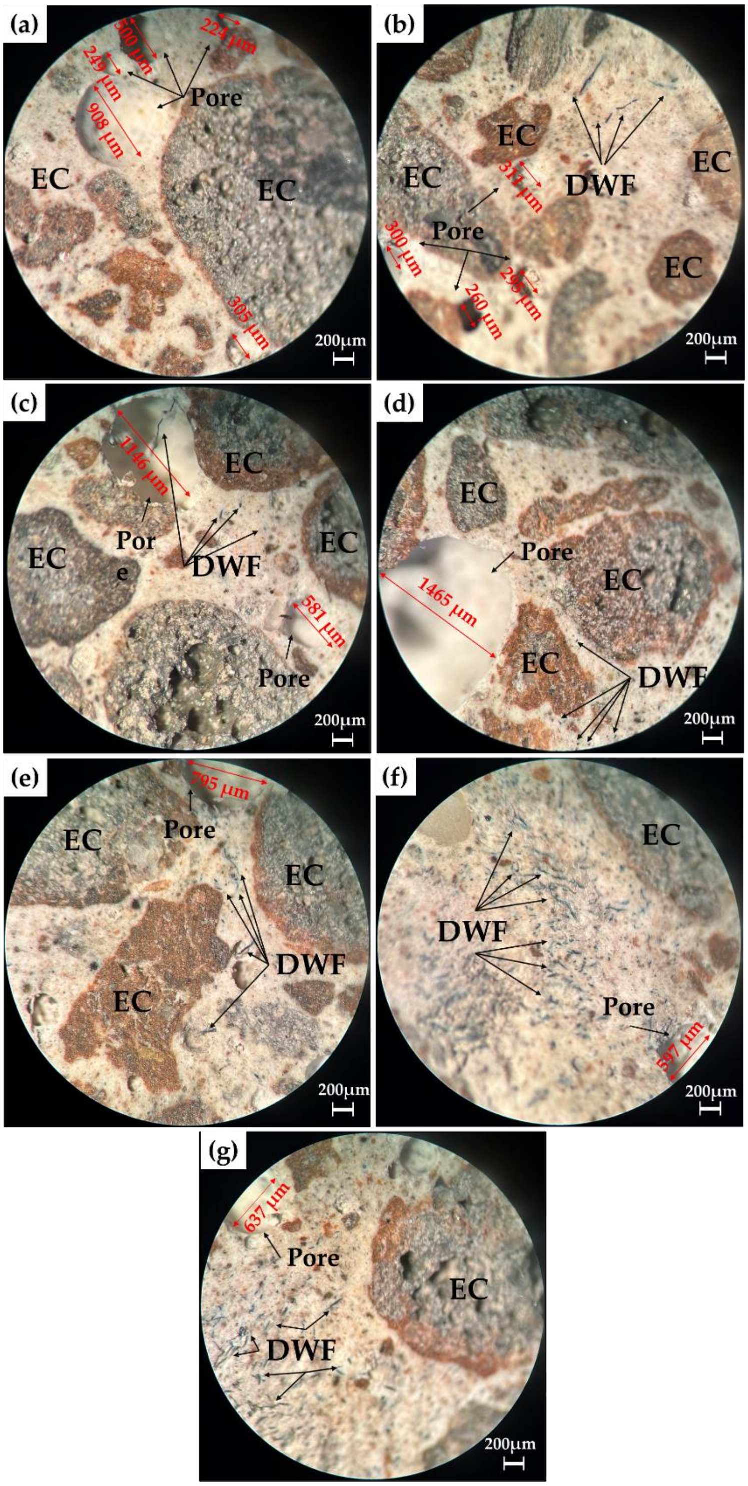

Figure 7. Cross-section and photomicrographs of CLCMs: **(a)** DWF0, **(b)** DWF025, **(c)** DWF050, **(d)** DWF075, **(e)** DWF100, **(f)** DWF125, **(g)** DWF150.

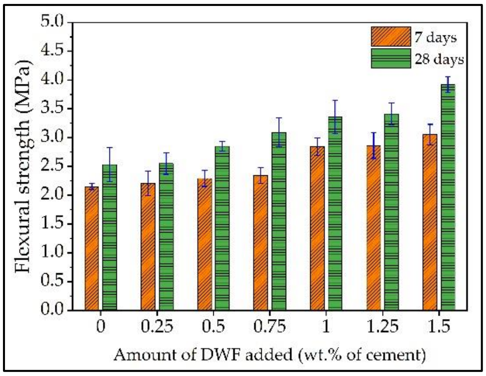

Figure 8. Flexural strength development of CLCMs at different DWF addition levels.

When the DWF usage rate was 0.25%, 0.50%, 0.75%, 1.00%, 1.25%, and 1.50% by weight of cement, the flexural strength of the test specimens increased by 2.79%, 6.51%, 8.84%, 32.09%, 33.02%, and 41.86%, respectively, compared to the reference mix after being subjected to a 7-day curing period. A similar trend was observed in the composite mortars subjected to a 28-day curing period, with the flexural strength values of these test specimens increasing by 0.79%, 12.65%, 22.13%, 32.81%, 34.78%, and 54.94%, respectively, compared to the reference mix. Each proportion of DWF used in this study contributes to an increase in flexural tensile strength. Furthermore, the highest increase in flexural strength (almost 55%) was exhibited by the series with the highest usage rate of DWF, which is the DWF150 mixture containing 1.50% DWF by weight of cement. Kalkan and Gündüz (2022) observed an improvement in flexural strength with the use of short textile waste fibres in lightweight mortar up to 2% by total weight of the mixture. Similarly, Kalkan and Gündüz (2016) observed an improvement in flexural strength by utilizing waste denim fibres in composite mortars with pumice and expanded perlite aggregates. The enhancement in flexural tensile strength resulting from the inclusion of DWF can be attributed to the high aspect ratio of the fibres. Additionally, this increase in strength can be attributed to the formation of a fibre/matrix structure, which provides additional load-bearing capacity and protects the structure from micro-cracking (Banthia & Sheng, 1996). In fact, as observed in Figure 6, there is a strong compatibility between the cement matrix and waste denim fibres, with a dense and void-free fibre-cement interface. These positive effects have contributed to the development of flexural strength by positively influencing the load transfer between the matrix and fibres and preventing crack development at certain level.

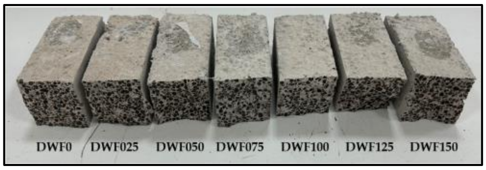

Figure 9. Test specimens.

Figure 10 illustrates the relationship between the compressive strength of the composite mortars being studied and the level of DWF addition.

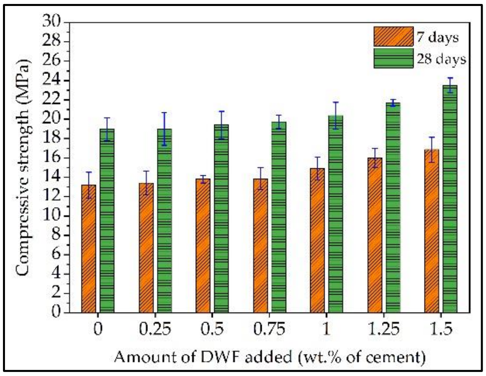

Figure 10. Compressive strength development of CLCMs at different DWF addition levels.

The compressive strength at 7 and 28 days followed a similar trend, as depicted in Figure 16. It was observed that the compressive strength increased in all DWF addition levels. The reference mix (DWF0) exhibited compressive strength values of 13.18 MPa and 18.98 MPa after 7 and 28 days of curing, respectively. Similar to the findings of the flexural tensile strength, the DWF150 mixture demonstrated the highest compressive strength values, reaching 16.85 MPa and 23.49 MPa after 7 and 28 days of curing, respectively. Furthermore, it has been observed that as the DWF addition rate increases, the compressive strength values of the test specimens also increase. Gonilho-Pereira et al. (2013) stated that despite the impact of waste fibre content on the evaluated mechanical parameters in cement-based mortars does not show a consistent trend, the use of 0.25% waste fibres (cotton and synthetic component) has improved the flexural and compressive strengths. When the literature is examined, the deterioration of compressive strengths of fibre-reinforced cementitious products is attributed to the porous structure that arises due to increased fibre-matrix incompatibility and worsened workability along with the addition of fibres (de Azevedo et al., 2021; De Azevedo et al., 2020; dos Santos Alberton et al., 2023; Safiuddin et al., 2021). On the other hand, as shown in Figure 6, in this study, it has been determined that the fibre-cement matrix interface is highly dense and void-free, and the fibre-matrix compatibility is also found to be quite high. Thus, with the presence of fibres, each fibre inhibits the formation of microcracks, leading to an increase in compressive strength (Fediuk et al., 2017; Rodier et al., 2020).

The load-displacement curves depicting denim waste fibre reinforced composites are presented in Figure 11. These curves were examined to determine the load and displacement values during the compressive strength test. The experiments were terminated when the load-bearing capacity decreased by 50% after reaching the maximum load for each series. According to the Figure 11, it is worth noting that in DWF-cement composites, the increase in fibre content resulted in not only an increase in the load carrying capacity but also significant enhancements in deformability or toughness. As the DWF content increased, a clear and distinct observation was made that both peak load carrying capacity and peak deformation values also increased. The deformation value of the reference composite mortar, which did not contain fibres, was approximately 0.175 mm, while the deformation values of the test specimens with added DWF increased by approximately 49% to reach approximately 0.26 mm at the end of the test. Thus, it was clearly observed that the addition of DWF increased the ductility and toughness. The significant improvement observed in DWF075, DWF100, and DWF150 can be attributed to the redistribution of load at the interface between fibres and the matrix, leading to a delay in crack propagation within the cement matrix. Therefore, fibres play a crucial role in inhibiting crack propagation within the matrix, thereby preventing the brittle failure typically observed in fibreless cement matrices. Similar findings have been reported by Martins et al. (2015), Zaid et al. (2021) and Sellami et al. (2022) in their investigations on soil-cement-sisal fibre composites, reinforced lime composites and diss fibre reinforced mortar, respectively.

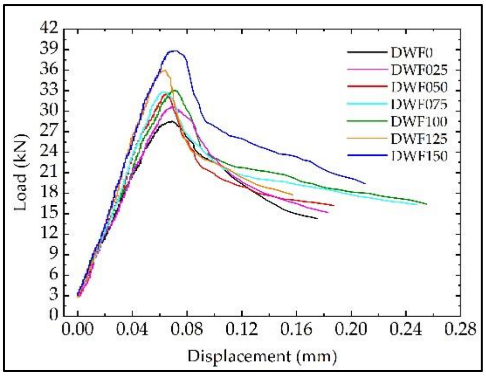

Figure 11. Load-displacement plot for DWF reinforced CLCMs.

4. Conclusion

This experimental study conducted a thorough investigation into the impact of incorporating denim waste fibers in cementitious lightweight composite mortars. Based on the test results, a decline was observed in the consistency and workability of cementitious mortars when denim waste fibers were added. This reduction of workability was due to the increased interlocking of the denim waste fibres and decreased free water because of water absorption of denim waste fibres. Capillary water absorption and permeable porosity of the cementitious lightweight composite mortars slightly increased due to both water absorption of the fibres and formation of pores because of worsen workability. Accordingly, fresh and hardened unit weight decreased in a certain level. The flexural and compressive strength increased for all DWF addition levels. Therefore, the optimum DWF usage rate for this study can be considered as 1.5% of the cement weight, which is the highest utilization rate. At 1.5% usage rate, CLCM's flexural strength increased by 54.94% and compressive strength increased by 23.76% compared to the reference specimen. As expected, the contribution of the fibres to the flexural strength was found to be higher than the compressive strength. According to the load-deformation analysis of CLCM specimens, it has been shown that denim waste fibres both increase the load carrying capacity and allow more deformation of the mortars. Thus, it was observed that the ductility and toughness of the mortars improved significantly.

It was determined before the start of the study that denim waste fibres consisted of high percentage of cotton fibres and lower percentage of synthetic fibres. As a suggestion for future studies, since it is unlikely that denim waste fibres will have a standard cotton-synthetic blend ratio, these blend ratios can be expressed at certain intervals and the physical and mechanical property evaluations of cement-based products can also be expressed at certain intervals.

In lightweight mortars, since the aggregates used are lightweight aggregates, their strength is relatively lower. For this reason, reinforcing the cement matrix with short fibres is the easiest and most preferred method for mechanically reinforcing lightweight mortars.

The results obtained from this study showed that denim waste fibres can play a significant role in the reinforcement of cementitious lightweight composite mortars.

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