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Structural Strength Properties of Waste Textile Fiber Reinforced Cementitious Lightweight Composite Mortars

Şevket Onur KALKAN*[1], Lütfullah GÜNDÜZ[1]

Abstract

This study aims to investigate the utilization of recycled textile waste fiber (RTWF) as fiber reinforcement in cementitious lightweight composite mortars. The effect of RTWF percentage on cementitious lightweight composite mortar (CLCM) consistency, plastic and dry set density, splitting tensile and compressive strength was measured. In particular, the effect of RTWF percentage on the structural mechanical properties of hardened mortar was examined in detail. Mohr-Coulomb Failure Criterion was used to examine the structural strength properties of composite mortars. Failure angle, internal friction angle, normal and shear strength and cohesion of RTWF reinforced composite mortars were investigated. Three different types of fibers were used including cotton-polyester mixture (Type 1), only polyester (Type 2) and cotton-polyester-acrylic mixture (Type 3). Different percentages of fibers, i.e. 1%, 2%, 3%, 5% and 7%, were added to CLCM. Test results showed reduction in dry set densities compared with the control specimen. It has been determined that the use of 1 % fiber improves the mechanical properties of light mortars. On the other hand, decreasing trend was observed in compressive and splitting tensile strength of mortars with higher amount of fiber usage. When structural strength properties were considered, same trend was kept. However, this research work has unique value from an innovative perspective in terms of evaluation of structural strength parameters.

Keywords: Waste textile fiber, lightweight, mortar, composite, structural strength, fiber reinforcement

1. INTRODUCTION

Construction sector is one of the most widely resource of material user industry. Therefore, more effective raw materials should be used in producing construction materials. Recycling materials and/or reusable materials are effective materials in terms of sustainability. One of these materials is textile waste fiber. Textile production in worldwide scale is more than 88.5 million tons per year. Large amount of waste from textile industry and discarded textile products after used are disposed worldwide. Textile industry produces around 12 million tons of waste in a year in Europa. Some of the wastes are turned into yarn at the recycling factory. However, fibers in very small sizes are created as waste products in this recycling process. Such textile waste fiber or textile waste cuttings are burned in various plants [1, 2]. Thus, they are damaging to the environment because they are

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non-biodegradable, or they are burned. In fact, this large amount of textile waste fiber accumulation creates an opportunity for the use of textile wastes in construction materials. Textile and garment industry is one of the main sectors that receiving driving force in the booming economy of Turkey. According to 2014 data, Turkey is the third country among European countries on textile export. Also, it is the world's sixth largest garment exporter. With such a large production capacity, waste and/or residual materials are composed depends on the production in Turkey’s textile sector. It can be seen that some of these materials are used in the internal components of the sector as a recycling material again. However, also the accumulation of waste fiber amount leftover from the recycling process can not be underestimated. The use of waste materials in the construction industry is gaining increasing importance in recent years. These wastes are used in cementitious materials due to their various advantages such as thermal conductivity, sound insulation, structural reinforcement, to lighten composite, etc. One of these waste raw materials is the textile waste fiber. Nowadays, the use of these materials could be investigated more in the cementitious composites, in the economical and sustainable points of views.

The use of fiber in concrete in developed countries began in the early 1960s and the use of fiber-reinforced concrete applications has been increased [3]. It can be seen that in the literature, various types of fibers are used as reinforcement element in cementitious composites. Various studies about fiber reinforcement in cementitious composites according to different advantages of the fibers as follows; steel fibers [4, 5], polypropylene fibers [6, 7], glass fibers [8, 9] and organic fibers, such as sisal [10, 11], coconut and oil palm [12], banana [13], etc. Though textile reinforced cementitious composites are frequently studied in order to strengthening masonry walls and concrete sections [14-18], studies on the usage of waste textile fibers in cementitious composites have not been investigated enough. In the literature, waste carpet fiber use as reinforcement material is seen more [19-21] than other types of waste textile fibers such as cotton [2, 22], polypropylene [23] and acrylic [24, 25].

Due to the increasing use of waste materials in the construction industry, it is predicted that advanced engineering properties should be examined in depth. For this purpose, the structural mechanical properties of the specimens carried out, i.e., the structural strength, are tested. Internal friction angle, failure angle, normal strength, shear strength and cohesion were predicted as structural strength parameters by the authors. Structural strength analysis of materials provides more comprehensive information about the material. Also, it can be obtained from structural strength parameters better understanding about what happens inside the material before it reaches fracture. For example, normal strength gives the strength value when the first crack occurs while loading the material. Mohr Coulomb Failure Criterion was tried to use to determine the structural strength properties of the specimens. Mohr Coulomb Failure Criterion could be estimated by some mechanical properties of concrete based on the tension and compression. Although a few Mohr Coulomb failure criterion practices related with concrete can be seen in the literature [26, 27], there are no such studies related to cementitious mortars.

Also, the usage of lightweight aggregates shows an increasing trend thanks to reduce dead load and provide insulation in the construction industry. Lightweight aggregates can be divided into two: organic cellular such as expanded polystyrene foam (EPS), extruded polystyrene foam (XPS) and polyurethane foam and inorganic cellular from natural and artificial sources such as expanded perlite, expanded clay, exfoliated vermiculite, etc. [28, 29]. Cementitious lightweight composite mortar normally created by these lightweight aggregates such as pumice, perlite, expanded clay, vermiculite, or air entraining agents [30].

Lightweight aggregates have a wide weight range distribution from 80 to 900 kg/m^3 [31]. According to TS EN 998-1 [32] a lightweight mortar is required to have a dry hardened density of less than 1300kg/m^3.

In this study, the use of short-dimensional textile recycling waste materials as reinforcement in cementitious mortars was investigated. Effect of short-dimensional recycled textile fibers on CLCM is a developing subject and a few studies available about this topic in the literature. Furthermore, this investigation can be interesting from technical point of view because any study of the structural strength properties of cement mortar cannot be found in the literature.

The study presented in this paper reports a research on the behavior of cement-based lightweight composite mortar produced by mixing EN 197-1 CEM I 52.5R white cement with various ratios of RTWF. Compressive strength values of specimens were obtained from compressive strength tests on cubic specimens and splitting tensile strength values of the specimens were obtained from Brazilian Test on cylindrical specimens.

In this study, a total 16 mortar mixtures were casted, and it was aimed to have the internal strength values of the materials produced by combining these two parameters, compressive strength and splitting tensile strength, through the Mohr circles.

2. EXPERIMENTAL WORK

2.1. Materials Used in the Study

In this experimental work, White Ordinary Portland cement (PC) conforming to EN 197-1 CEM I 52.5R white was used as binder material. Since the fibers used in the study are textile waste fibers, they have different colors. The reason for using white cement in this study is to see the coloration of the final product due to the colors of the waste textile fibers (Fig.1). The chemical composition of the white Portland cement is shown in Table 1. The X-ray Fluorescence (XRF) analysis was used to determine mineralogical composition of the aggregates, lime, and cement. Also, physical and mechanical properties of white Portland cement are shown in Table 2.

In this study, pumice was evaluated as the main aggregate. Also, due to low unit volume weight of pumice, it was used as lightweight aggregate in this experimental work. Pumice is a geological material, and it has spongy and porous structure. Pumice contains numerous pores, because during the formation, gases in the structure in the pumice rapidly leave the body and then sudden cooling takes place. Thus, the porous structure occurs. Disconnected hollows generally form these pores. Therefore, pumice has low permeability, and it has very high thermal and sound insulation. Because of these characteristics, pumice is widely used as a lightweight aggregate in lightweight concrete designs. Besides, pumice is used in production of lightweight building elements such as bricks, masonry blocks, panels, and boards, etc. [33].

Table 1 Chemical composition of WPC, NPA, HPL and EP

Major element	PC (%)	NPA (%)	HPL (%)	EP (%)
SiO_2	21.60	74.10	< 1.3	72.20
Al_2O_3	4.05	13.45	0.4 – 0.8	11.40
Fe_2O_3	0.26	1.40	< 0.3	0.53
CaO	65.70	1.17	80	0.63
MgO	1.30	0.35	< 2	0.33
SO_3	3.30	-	< 2	1.87
Na_2O	0.30	3.70	< 0.8	3.3
K_2O	0.35	4.10	-	4.20

PC : White Portland Cement
NPA : Nevşehir Pumice Aggregate
HPL : Hydrated Powder Lime
EP : Expanded Perlite

Pumice aggregate used in this experimental work was supplied from a pumice mining quarry in Nevşehir-Turkey. Nevşehir pumice aggregate (NPA) was primarily crushed by a crusher and then screened into 0/0.5 mm as fine aggregate and 0.5/3 mm as coarse aggregate for this study.

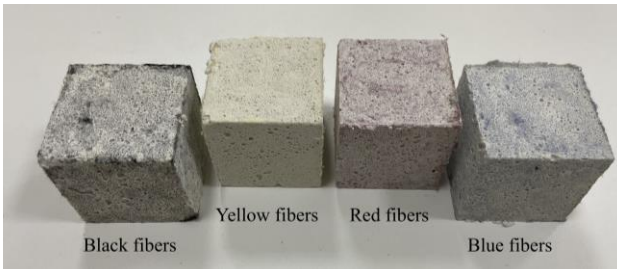

Figure 1 Mortar specimens produced using different colored fibers

Expanded perlite was used in this experimental work as lightweight aggregate. Expanded perlite as a commercial product used in this study was supplied from İzmir Region in a size of 0-2 mm. Any procedure was not applied to the material and was directly used in the CLCM combinations.

Table 2 Physical and mechanical features of PC

Specific gravity (g/cm^3)	3.06
Blaine specific surface (cm^2/g)	4600
Initial setting time (min)	100
Final setting time (min)	130
Volume expansion (mm/m)	1
Compressive strength (MPa)	
7 days	37.0
14 days	50.0
28 days	60.0

Perlite is a glassy and volcanic origin rock type. When perlite granules are heated in the temperature range between 900 °C and 1100 °C, its volume increases about 20 times and it becomes a porous structure. Resulting new material after heat-treating is called expanded perlite. This formal transformation or expansion makes expanded perlite a very lightweight material and very efficient thermal insulator. Expanded perlite aggregate is often used for these features when thermal insulation and lightness required cases are needed. In Table 1, the chemical component of the expanded perlite is also given.

Hydrated Powder Lime (HPL) was supplied as a commercial product in the sector. The HPL used in this study belongs to the CL80 category according to EN 459-1 standard. HPL additive was used in the mixture combinations in order to stabilize pH balance. The chemical content of HPL is given in Table 1.

The mixing water was regular tap water. Recycled textile fiber as a new type of reinforcement element is proposed in this study. Recycled textile fibers used in CLCM combinations were collected from denim factories in Uşak Region, textile recycling center of Turkey. In these factories, wastes are produced at three stages such as, production stage, ageing stage, and abrasion stages. Textile wastes produced after these stages are powder sized.

Three types of recycling waste are supplied from Uşak Region (Fig.2). First one is mixture of cotton waste fibers from recycling of cotton products and polyester waste fibers, the waste of plastic bottles during the conversion of PET bottles to textile fiber. Cotton fiber is a vegetable textile fiber. The main component of cotton fiber is cellulose with a ratio of 94%. The remaining of cotton fibers consists of hemicellulose, pectin and inorganic substances. While diluted bases minimal effect on cotton fiber, cotton fiber shows degradation with concentrated and strong acids. Cotton fibers do not exhibit degradation up to 150 °C [34, 35].


Figure 2 Fiber specimens

The second type of recycled textile waste fiber consists of fully polyester fibers. Polyesters fibers are chemical fibers with synthetic raw materials [35]. Polyester fibers can be obtained by recycling of PET (Polyethylene terephthalate) bottles. PET has usage areas such as soft drink, food and beverage containers, and polyester fibers. Polyester fibers are resistant to weak acids even at the boiling point. They have good resistance to strong acids at room temperature while poor resistance to strong bases. Melting point of polyester fibers is 250 °C [34, 35].

The last type of RTWF is mixture of cotton waste fiber, polyester waste fiber and acrylic waste fiber, the remaining waste from the recycling stage of the acrylic products were made from synthetic fibers. Acrylic fibers are obtained by mixing ratio of 85 % acrylonitrile polymers and more than one monomer with a ratio of 15 %. Acrylic fibers are resistant to other acids except nitric acid. Especially dense and hot state alkali damages the fibers. There is not a certain melting point of the acrylic fibers. Melting point of them ranges from 215 to 255 ° C [35].

Recycled textile waste fiber (RTWF) was used in this research to improve mortar’s physical and mechanical properties. Any pretreatment was not applied to the RTWFs used. Physical properties of RTWFs are given in Table 3.

Table 3 Physical properties of fibers

Color	Blue, white, black, pink
Fiber length (μm)	< 200
Fiber diameter (μm)	<20
Specific gravity of cotton (g/cm^3)	1.50-1.55
Specific gravity of polyester (g/cm^3)	1.38
Specific gravity of acrylic (g/cm^3)	1.14-1.20
Water absorption capacity of cotton	25-27 %
Water absorption capacity of polyester	0.2-0.8 %
Water absorption capacity of acrylic	0.30-1.30 %

2.2. Mortar Mix Design

Mixture proportioning of the CLCM combinations for this experimental study is shown in Table 4. Sixteen different cementitious mortar combinations were prepared and analyzed in order to observe the possible effect of utilizing very fine sized textile waste fibers on CLCMs. The amount of cement ratio was kept constant as 33 % by weight for all mixture combinations.

Table 4 Mortar combinations and mix design

	PC (wt.%)	NPA (wt.%)	EP (wt.%)	Fiber (wt.%)	HPL	w/s	w/c
LF-R	33.0	48.0	10.0	0.0	9.0	0.50	1.52
LF1-1	33.0	47.0	10.0	1.0	9.0	0.51	1.55
LF1-2	33.0	46.0	10.0	2.0	9.0	0.60	1.82
LF1-3	33.0	45.0	10.0	3.0	9.0	0.69	2.09
LF1-5	33.0	43.0	10.0	5.0	9.0	0.80	2.42
LF1-7	33.0	41.0	10.0	7.0	9.0	0.97	2.94
LF2-1	33.0	47.0	10.0	1.0	9.0	0.55	1.67
LF2-2	33.0	46.0	10.0	2.0	9.0	0.67	2.03
LF2-3	33.0	45.0	10.0	3.0	9.0	0.75	2.27
LF2-5	33.0	43.0	10.0	5.0	9.0	0.97	2.94
LF2-7	33.0	41.0	10.0	7.0	9.0	1.18	3.58
LF3-1	33.0	47.0	10.0	1.0	9.0	0.56	1.70
LF3-2	33.0	46.0	10.0	2.0	9.0	0.68	2.06
LF3-3	33.0	45.0	10.0	3.0	9.0	0.76	2.30
LF3-5	33.0	43.0	10.0	5.0	9.0	0.93	2.82
LF3-7	33.0	41.0	10.0	7.0	9.0	1.10	3.33

Again, the amount of the expanded perlite and hydrated powder lime ingredients in all mixes was kept constant as 10 and 9 % by weight, respectively. Within the scope of the study, the mixture design was evaluated by weight. In order to keep the total mixture amount constant as 100%, the amount of fiber added to the mixtures by weight was removed from the pumice aggregate in the same proportion.

First mortar mixture, which is named as LF-R, was analyzed as a reference mortar and this mixture does contain RTWF additive. This mix actually was considered to understand the impact of textile waste fiber to the mortar’s properties.

In order to examine the physical and mechanical properties of CLCMs reinforced with different types of fibers, three different types of RTWF were studied in this research. First five mixtures (LF1-1, LF1-2, LF1-3, LF1-5, LF1-7) were mixed with combination of cotton and polyester fibers and this group is going to be named as Type 1 RTFW, second five mixtures (LF2-1, LF2-2, LF2-3, LF2-5, LF2-7) were mixed with only polyester fibers and this group is going to be named as Type 2 RTWF and the last five mixtures (LF3-1, LF3-2, LF3-3, LF3-5, LF3-7) were mixed with combination of cotton, polyester and acrylic fibers and this group is going to be named as Type 3 RTWF, in this work.

In order to determine the water demand for each mixture separately and to provide the same workability for each mixture, flow table test was carried out by the requirements of the ASTM C 1437-13 standard. The water/solid ratios were changed from 0.50 to 1.18. The water-solids ratio investigated in this research can be defined as the ratio of total mass of water to the total mass of solids (cement, lime, aggregates, and fibers). Mixing was carried out by a mortar mixer. Then, the fresh cement mortar specimens were placed into the molds and left for 24 hours. Subsequently, specimens were removed from the molds and placed in wet surface curing condition (21 ± 1 ˚C and 95 % RH) for the first 3 days and after that the specimens were left to dry in a normal air condition (21 ± 1 ˚C and 40 % RH) to the testing time (7 and 28 days).

In this work, the influence of RTWF was investigated in the usage of simultaneously, 1, 2, 3, 5 and 7 %. The fresh mortar properties such as consistency and fresh density were studied. 7- and 28-days compressive strength of mortars were investigated. Also, splitting tensile strength of hardened mortars were tested on 28 days. Compressive and splitting tensile strength tests were conducted on 50x50x50 mm cubic test specimens and Ø50x100 mm cylindrical test specimens, respectively. Compressive and splitting tensile strength were determined as the average of 3 specimens test results. Structural strength values of the CLCMs have been achieved through splitting tensile and compressive strength tests by using Mohr Circles.

3. TEST RESULTS AND DISCUSSION

3.1. Flow and Water Demand

The flow diameters and water demand of mortar mixtures were analyzed on fresh mortar specimens. The water to solid ratio (W/S) of all mixtures is shown in Table 4. The W/S of the mixtures were changed from 0.50 to 1.18 based on the RTWF amounts. Flow diameters of mixtures were calculated according to ASTM C1437-13 standard with flow table test and were given in Figure 3. In the study, when the water/solid ratio is fixed, there are great problems in the mixing and molding stages of the mortars using high fiber ratios. For this reason, mortars with similar workability were produced by keeping the flow diameters constant in all mixtures. The flow diameters of all mixtures were fixed to be 142 ± 5 mm. For all three types of fiber, the mixing water was increased depending on the fiber ratio in order to provide a similar workability in fresh mortars.

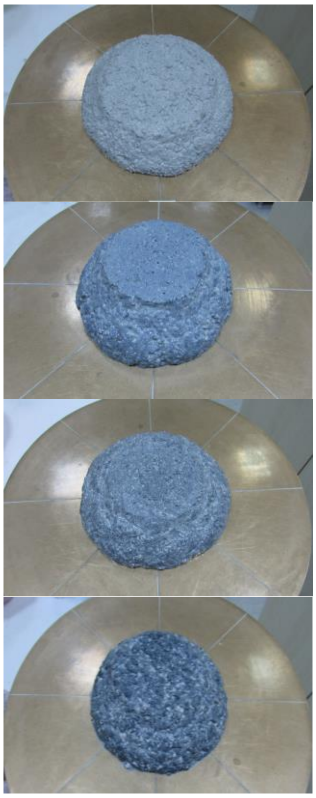

Figure 3 Flow diameter of CLCMs versus RTWF percentage of CLCM specimens

3.2. Fresh and Hardened Densities

With the increase of the W/S ratio, in plastic unit weight changes were not observed too much. However, despite the increase in W/S ratio, gradually decreasing at dry set densities was recorded in all three types of RTWF mixtures (Table 5). This is because the fibers have fluffy structure and thus, bring more unit volume to the mortar. The fresh density of cement mortar specimens was varied between 1055 kg/m^3 and 1184 kg/m^3 based on the percentage of RTWF ratio. Dry set density values were varied between 611 kg/m^3 and 959 kg/m^3. Compared to the control specimen, Type 1, Type 2 and Type 3 mixtures containing 1.0 % fiber were found 1.04 %, 3.75 % and 5.94 % lighter, respectively. The same case was observed at 7 % RTWF containing mixtures. They were found 23.15 %, 36.29 and 32.74 % lighter than unit volume weight of control specimen. It is stated that in TS EN 998-1 standard [32], lightweight mortars should be lighter than 1300 kg/m^3. In this research, it was reached much better results than this value.

Table 5 Physical and mechanical properties of mortars

Mix	Flow (mm)	Fresh density (kg/m^3)	Hardened density (kg/m^3)	28-days compressive strength (MPa)	28-days splitting tensile strength (MPa)
LF-R	154	1159	959	4.89	0.83
LF1-1	142	1143	949	6.88	1.05
LF1-2	130	1164	902	5.64	0.96
LF1-3	120	1184	854	4.38	0.86
LF1-5	112	1393	816	4.06	0.68
LF1-7	110	1254	737	2.58	0.47
LF2-1	146	1124	923	5.77	0.68
LF2-2	138	1120	830	3.30	0.51
LF2-3	136	1142	794	2.53	0.44
LF2-5	131	1121	708	1.38	0.30
LF2-7	126	1055	611	0.82	0.25
LF3-1	141	1147	902	5.48	0.87
LF3-2	130	1138	850	3.77	0.55
LF3-3	128	1135	800	2.88	0.47
LF3-5	120	1123	730	1.98	0.36
LF3-7	112	1138	645	1.27	0.30

3.3. Compressive Strength

Compressive strength is the ability to resist the show to break the material under axial load impact. The compressive strength tests were conducted according to EN 1015-11 standard. In the compressive strength tests, cubic specimens were used for each batch. The specimens, after removal from the molds and cured in water for 3 days and then dried at room temperature until the testing time, were taken directly on the compressive strength test without any further action. The 7- and 28-days compressive strength values of all mortar mixtures are presented in Figure 4 and Figure 5 based on percentage of RTWF usage by weight, respectively.

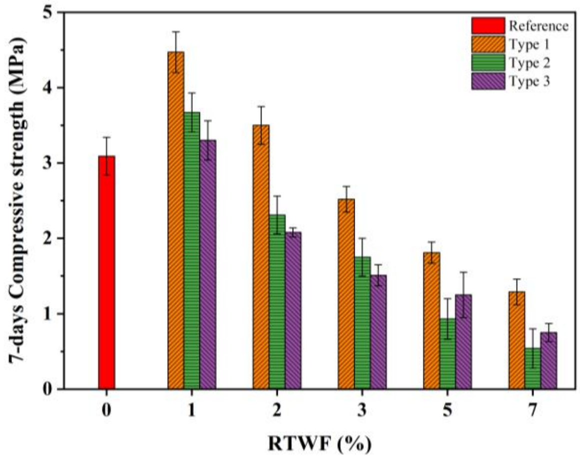

Figure 4 Compressive Strength versus RTWF percentage of CLCM specimens on 7 days curing time

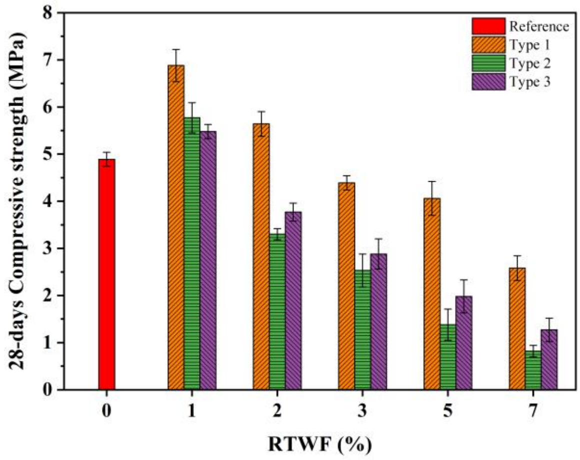

Figure 5 Compressive Strength versus RTWF percentage of CLCM specimens on 28 days curing time

The results showed that compressive strength of mixture combinations was decreased with increase in fiber content in both 7 days and 28 days curing time. One reason for this is that the fibers agglomerate with the increase in the fiber content, and another reason is that with the increase in the fiber content, the amount of mixing water increases and the water/cement ratio decreases. On the other hand, at 1 % fiber usage rate, all three types of fibers improved the compressive strength of lightweight mortars. In addition, Type 1 fibers with a fiber usage rate of 2 % are also effective in improving the compressive strength. With the addition of 1 % fiber to the lightweight mortars, the compressive strengths of the mortars with the addition of Type 1, Type 2 and Type 3 fibers were improved by 40.70 %, 18.00 % and 12.07 %, respectively, compared to the reference mortar. However, above 1 % usage for Type 2 and Type 3 fibers, and above 2 % of Type 1 fiber, the compressive strength tends to decrease, and the compressive strengths remain below the compressive strength of the reference mortar with the increase in fiber usage ratio. The reason can be regarded as, because fiber usage causes an increase in volume of mortar, unit volume weight of mortar decreases, and this decrease creates lighter unit volume weight. This action causes a return of loss of compressive strength, as mentioned before. The other reason for these reductions is that the use of high fiber content reduces the workability of the mortar. To fix the workability of mortars, extra mixing water added to the fresh mortars, and extra water increased the w/c of the fresh mortar. Increasing w/c caused a decrease in compressive strength. Also, agglomeration occurs as a result of the effect of its distribution and orientation of fibers in the mortar. Studies have shown that the fiber fraction can affect the compressive strength of concrete by 25%, either positively or negatively [36, 37].

Analyzing Figure 5, compressive strength values of specimens with 28 days curing time were found higher than 7 days curing time specimens, as it should be. When examined according to fiber types, it is seen that the specimens mixed with Type 1 RTWF has the highest compressive strength. Comparing 1 % fiber usage specimens for 28 days compressive strengths, Type 1 RTWF content specimens can be described as the best and Type 2 and the last one is Type 3. However, above 1% of fiber usage, it was observed that Type 3 RTWF content mixtures have greater compressive strength values than Type 2 RTWF content mixtures. As previously mentioned, Type 1 contains cotton and synthetic fibers, Type 2 contains only synthetic fibers and Type 3 contains mostly synthetic and a small amount of cotton fibers.

Having studied the compressive strength values, specimens containing cotton fibers appear to be higher compressive strength values. This phenomenon can be explained as; cotton fiber makes better bonds with the mortar.

When viewed under a microscope, face of the synthetic fibers seems to be rounded shape and smooth surface. On the contrary, surface of cotton fibers is rough and they have volute structure (Fig. 6a and 6b). Therefore, it can be said that cotton fibers can hold the mortar better.

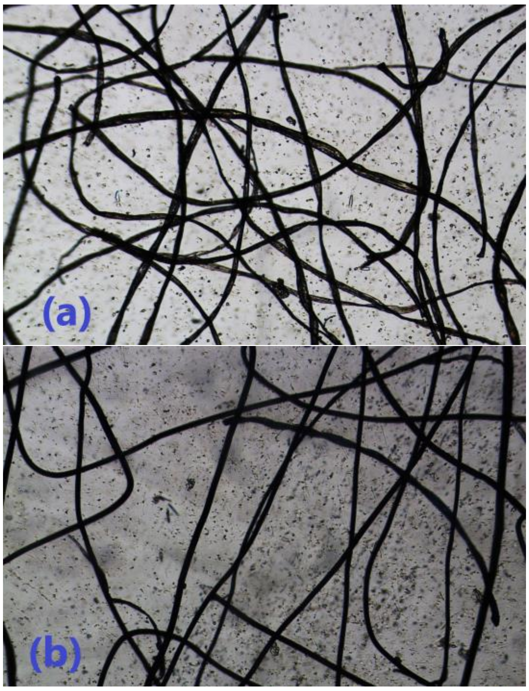

Figure 6 Microscope view of the cotton (a) and synthetic (b) fibers.

28 days compressive strength classification of cement mortars are grouped in 4 different classes in TS EN 998-1 standard. These compressive strength classes are;

- CS I (0.4 – 2.5 N/mm^2),
- CS II (1.5 – 5.0 N/mm^2),
- CS III (3.5 – 7.5 N/mm^2)
- CS IV ($\geq$6 N/mm^2).

When compressive strength values of CLCM specimens is evaluated according to the prescribed categories in TS EN 998-1 standard, it was observed that the 28 days curing time compressive strength values for 1% and 2% fiber utilization in CLCM ensure the compressive strength of 3.5 N/mm^2 for CS III class and the strength values drop to CS II class between 3 % and 5 % fiber utilization and 7 % fiber usage in CLCM drops the compressive strength class for CS II to CS I. In fact, even the lowest compressive strength value (0.54 N/mm^2) at 7 days curing time ensures CS I class foreseen in TS EN 998-1 standard (Fig. 3).

3.4. Splitting Tensile Strength

The simplest and most frequently applied method used to determine the tensile strength of concrete is splitting tensile test also known as the Brazilian Test. This test provides a lower coefficient of variation. In splitting tensile test, same materials and equipment are used with compression test. This test is performed by applying a diametric compressive force along the length of a cylindrical specimen between two plates [38-40].

The splitting tensile strength, T, can be calculated by the following Equation (1):

$$T = \frac{2P}{\pi L d} \quad (1)$$

Where, T is splitting tensile strength in N/mm^2, P is peak load in N, d is diameter of specimen in mm and L is length of specimen in mm.

For the splitting tensile strength testing, cylindrical specimens, with dimensions of Ø50x100 mm, were used for each batch. The specimens, after removal from the molds, they cured at 3 days in a wet surface condition and then dried at room temperature until the testing time. They were taken directly on the test without any further action after 28 days curing time. 28 days splitting tensile strength results of all mortar mixtures are given in Figure 7 based on weight percentage of RTWF usage.

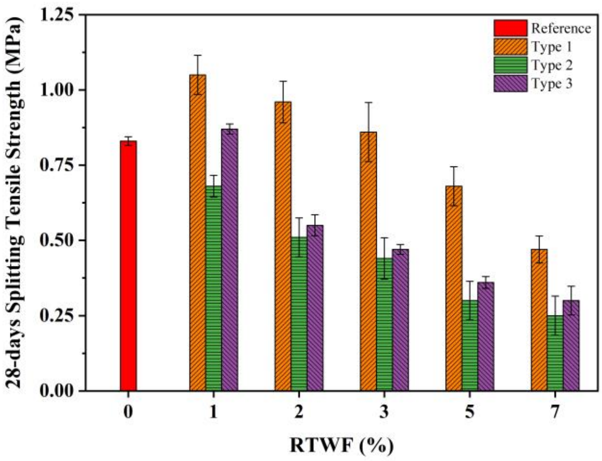

Figure 7 Splitting Tensile Strength versus RTWF percentage of CLCM specimens on 28 days curing time

As analyzing Figure 7, it can be easily seen that the owner of the better values is Type 1 RTWF. Type 2, which has only polyester fiber content in it, comes after Type 1 and Type 3 RTWF, exhibits the worst splitting tensile strength values. The mixture of different fibers provides more improvement effect on the tensile strength of hardened mortars. These fibers are the wastes that occur while producing yarn from textile wastes. Therefore, these fibers are woven fibers. However, only polyester fibers (Type 2) are obtained from pet bottles and are non-woven. Therefore, the strength of composite fibers is higher (Type 1 and Type 3). As a general acceptance, compressive strength and splitting tensile strength are proportional to each other. This phenomenon can be clearly observed from the results of compressive strength and splitting tensile strength experiments. Having 1 % fiber content specimens have the highest splitting tensile strength values as they have in the compressive strength. Likewise, having 7 % fiber content specimens have the lowest splitting tensile strength values as they have in the compressive strength.

In cementitious composites, there is a relation between strength values and unit volume weight of composites. This relationship is given in the Figure 8. In this figure, relation between compressive strength and unit volume weight and relation between splitting tensile strength and unit volume weight are given.

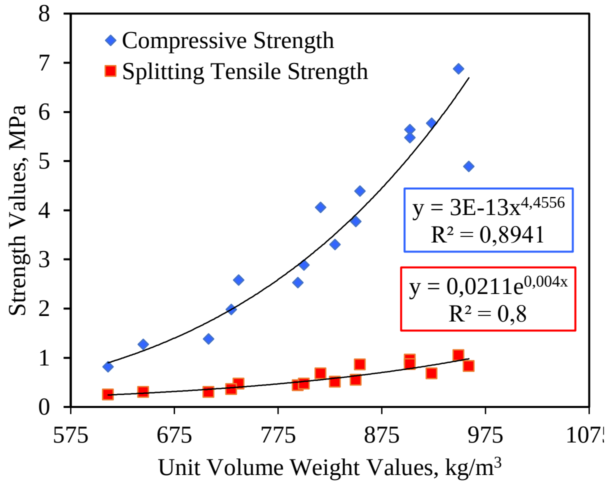

Figure 8 Strength versus Unit Volume Weight of CLCM specimens

According to Fig. 7, both compressive and splitting tensile strength and unit volume weight relations were obtained as increasing in a form of power function. According to this function, when the unit volume increases, both the compressive strength and the splitting tensile strength have been shown to increase.

3.5. Structural Strength Properties

Structural mechanical properties, which are internal friction angle, failure angle, normal strength, shear strength and cohesion parameters, of the specimens were carried out in this study. Structural strength analysis of materials provides more comprehensive information about internal actions of the material.

Mohr Coulomb Failure Criterion was used to determine the structural strength properties of specimens. Mohr Coulomb Failure Criterion can be estimated some mechanical properties of concrete based on the tension and compression stresses.

Mohr envelopes were drawn by the use of the compressive and splitting tensile stress data. One examples of drawn Mohr envelopes is given in Figure 9. These drawings have been done separately for each mixture combination and structural mechanical properties of the materials have been found through the drawings.

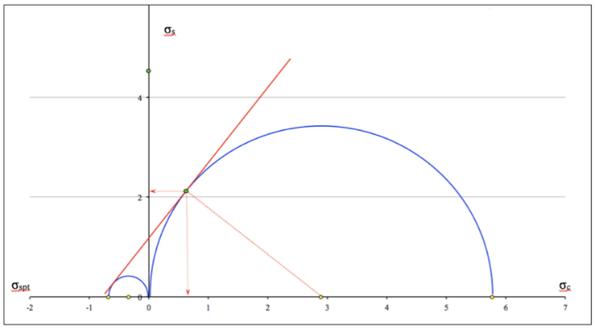

Figure 9 Mohr Circle drawing of LF6

Firstly, a coordinate system, which x plane represents normal strength and y plane represents shear strength, is drawn. Mohr circles were generated by plotting a half circle to the left of the x-axis of the coordinate system representing splitting tensile strength and another half circle to the right of the x-axis of the coordinate system representing compressive strength. Then, a tangent line is drawn to the two half circles. The slope of this line gives the internal friction angle of the material. The point where the tangent line cut the y plane gives cohesion. Center of the compressive strength and tangent line are joint by a straight line. Value of this point at x-axis gives normal strength and at y-axis shear strength. In this study, these values are discussed as structural strength values.

Structural strength parameters are chiefly used in rock mechanics and soil mechanics. Internal friction angle, failure angle and cohesion parameters are the main parameters in rock and in soil classification and load bearing calculations. Mohr coulomb criterion is used to obtain these parameters. With a similar approach, in order to find these parameters and to understand the inner structure of cementitious mortars, Mohr Coulomb criterion was used. Structural strength properties of CLCMs are given in Table 6.

Table 6 Structural mechanical properties of the CLCMs

Mix	α (°)	ϕ (°)	σ_n (MPa)	C (MPa)	σ_s (MPa)
LF-R	66.5	43.0	0.79	1.13	2.24
LF1-1	68.0	46.0	0.99	1.35	2.35
LF1-2	67.0	45.0	0.88	1.17	2.03
LF1-3	66.0	42.0	0.73	1.00	1.64
LF1-5	67.5	45.0	0.59	0.82	1.40
LF1-7	66.0	44.0	0.41	0.58	0.95
LF2-1	71.0	52.0	0.69	1.00	1.98
LF2-2	68.5	47.0	0.46	0.65	1.13
LF2-3	66.5	45.0	0.41	0.54	0.92
LF2-5	64.0	41.0	0.26	0.33	0.54
LF2-7	60.0	32.0	0.20	0.23	0.35
LF3-1	68.5	47.0	0.73	1.10	1.85
LF3-2	68.5	48.0	0.50	0.72	1.26
LF3-3	67.5	45.0	0.44	0.60	1.01
LF3-5	66.5	44.0	0.31	0.43	0.72
LF3-7	64.0	38.0	0.25	0.31	0.50

α: Failure Angle
ϕ: Internal Friction Angle
σ_n: Normal Strength
C: Cohesion
σ_s: Shear Strength

In rock mechanics, the value of failure angle mostly depends on formation type of the rock. Whereas failure angle is steeper in hard and brittle rock, it is less inclined in other words; value of failure angle is smaller, in the soft and ductile rock types. In particular, the value of the failure angle is very small in the formations that can be easily slide, such as sand. The same approach may be valid for cementitious compounds. When examining Table 6, decreasing trend was observed in failure angle of CLCMs with an increase in the amount of fiber content in the mixtures. In the fiber usage from 1 % to 7 %, failure angle of Type 1 fiber mixtures decreased 2 degrees, 11 degrees decrease was seen in Type 2 fiber mixtures and 4.5 degrees declining was observed in Type 3 fiber mixtures. Therefore, use of Type 2 fiber in mixtures could be said to make the mortar more ductile. When the fibers are included into the cement mortar, it loses its brittle property and it becomes more flexible structure. Therefore, as the acceptance of rock and soil mechanics, failure angle values of the CLCMs are decreased because of the increase of their flexibilities. It can be seen in the table that the most ductile specimen was found as LF2-7 with a failure angle of 60 ° and the most brittle one was found as LF2-1 with a failure angle of 71 °.

Internal friction angle for a given material is the angle on the Mohr's Circle graph of the shear stress and normal stresses at which shear failure occurs. Researchers have used the internal friction angle in rock and soil classification. In soil classification, soils with less than 30° internal friction angle are considered as very loose and as the internal friction angle increases the classification continues as loose, compact, dense and very dense soil. Similar phenomenon can be seen in rock classification; rocks with internal friction angle less than 15° are called as very poor and as the internal friction angle increases the classification continues as poor, fair, good and very good rock. With this perspective, cementitious composites with higher value of internal friction angle could be evaluated as better-compacted materials. According to Table 6, internal friction angles of CLCMs decreases with increase in fiber content. CLCMs are becoming more loose structure with increase in RTWF content in the mortar combinations. Thus, it is thought that the loose mortar structure reduces the internal friction angle of the material.

The most compact specimen was found as LF2-1 with an internal friction angle of 52 ° and the loosest specimen was found as LF2-7 with an internal friction angle of 32 °.

The normal strength and shear strength is found, which cause the failure, by using the angle of slope of the plane of failure on Mohr Circle. Normal strength is the normal load to be carried by the material. Normal strength is the load that material could carry without deforming. Higher loading than normal strength of material causes deformation in the material. Up to normal strength that found by Mohr's Circle, deformation does not occur in the material. However, the material is permanently damaged between normal strength and compressive strength. In this case, it could be said that normal strength is the moment that material take the first damage. According to Table 6, it is seen that normal strengths of CLCMs have a decreasing trend depending on the reduction in splitting tensile and compressive strength in each type of mixtures. As it can be seen from the Table 6, normal strength parameter of Type 1 mixtures with highest value of 0.99 MPa (LF1-1) and lowest value of 0.41 MPa (LF1-7) are greater than the others as in splitting tensile and compressive strengths. Which means that Type 1 mixtures could resist more load before first deformation inside. As previously mentioned, according to TS EN 998-1 standard, minimum compressive strength of cementitious mortars must be at least 0.4 MPa. It is seen from Table 6 that normal strength values of almost all mixtures are less than the value (0.4 MPa) specified in TS EN 998-1 standard. In other words, the produces mixtures can provide the compressive strength condition prescribed in the standard even without any deformation inside the material.

Cohesion is the force that holds the particles of concrete or mortar together. Cohesion indicates that what extent materials that forming the concrete or mortar are connected to each other. Additionally, the strength of the mortar or cement paste is dependent on the cohesion of the cement paste and adhesion of cement paste with aggregate particles [41]. If an assessment is done with this approach, it could be said that decrease in strength parameters of produced mortar specimens is caused by the decrease in the cohesion parameter (Table 6). According to the cohesion values given in Table 6, it is easily observed that Type 1 mixtures have the best cohesion values and Type 2 mixtures have the lowest cohesion values. This phenomenon could be explained by the inability of cement to adhesion on the polyester fiber as previously discussed.
According to Mohr-Coulomb Criterion, factors that affect the shear strength are normal strength, cohesion, and internal friction angle. Besides, shear strength can be obtained by the Mohr's Circle. Decrease in internal friction angle and cohesion leads a reduction on shear strength parameter according to Mohr-Coulomb Criterion. This situation can be easily seen in Table 6. When the table is examined, Type 1 specimens exhibit the highest shear strength values. On the other hand, despite the reduction on shear strength parameters, specimens were gained flexibility characteristics against vertical and lateral loads by fiber content.

4. CONCLUSIONS

In this paper, a unique experimental work on the influence of RTWF additive on CLCMs' mechanical and structural strength parameters is reviewed and mainly presented. The results obtained from the study are summarized as follows:

1. As the RTWF is an industrial solid waste of textile recycling sector, this paper can be evaluated as an important piece of work on behalf of utilization of the waste. The results analyzed in this work present that the effect of adding of RTWF in the behavior of composite lightweight cementitious mortar is promising. It could be concluded that the use of RTWF can improve the ductility and flexibility of composite mortar. Produced CLCMs provides the criterions foreseen in TS EN 998-1 standard in terms of unit volume weight and compressive strength.

2. Type 1 fiber, which is the mixture of cotton and polyesters waste fibers, was found as more suitable in order to use it in lightweight composite mortars. It provided higher compressive and splitting tensile strength through its cotton content during the tests. It is thought that cotton fibers can fit to the mortar by its rough surface. Besides, it was found that Type 1 mixtures had better characteristics on structural strength parameters than Type 2 and Type 3 mixtures.

3. It has been determined that the use of 1 % of the fibers used in the study in lightweight mortars strengthens the mortar in terms of compressive and splitting tensile strength.

4. In all mixture combinations, increase in fiber ratio is improved the lightweight characteristics of cementitious mortars. The lightest mortars were seen as 7 % fiber content mortars in all types. The lowest unit volume weighted type was found as Type 2 mortars with unit volume weight range of 923-611 kg/m^3. If the specialties that lightness characteristics bring need to be examined in the future works, Type 2 fibers, which is a combination of cotton, polyester and acrylic fibers, could be examined.

5. Structural strength parameters, which are forming the main concept of this experimental research, were found by using Mohr's Circle. Mohr's Circles and Mohr-Coulomb Theory is widely used in soil and rock mechanics to understand the structural strength parameters of soils and rocks. Examples of this approach in concrete and/or mortar applications are not enough in the literature. Therefore, in this work, Mohr-Coulomb Criterion was tried to apply to lightweight composite mortars in order to understand the inner world of textile fiber reinforced cementitious mortars. Based on the results of the study, it was seen that Type 1 and 1% fiber usage gave better results in normal strength, cohesion, and shear strength parameters. The most ductile specimen was found as LF2-7 with a failure angle of 60 °. The most compact specimen was found as LF2-1 with an internal friction angle of 52 °.

This work could be evaluated as an important study to create a new research area as structural strength of cementitious composites.

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The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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