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Possibility of using waste tire rubber and fly ash with Portland cement as construction materials

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ABSTRACT

The growing amount of waste rubber produced from used tires has resulted in an environmental problem. Recycling waste tires has been widely studied for the last 20 years in applications such as asphalt pavement, waterproofing systems and membrane liners. The aim of this study is to evaluate the feasibility of utilizing fly ash and rubber waste with Portland cement as a composite material for masonry applications. Class C fly ash and waste automobile tires in three different sizes were used with Portland cement. Compressive and flexural strength, dry unit weight and water absorption tests were performed on the composite specimens containing waste tire rubber. The compressive strength decreased by increasing the rubber content while increased by increasing the fly ash content for all curing periods. This trend is slightly influenced by particle size. For flexural strength, the specimens with waste tire rubber showed higher values than the control mix probably due to the effect of rubber fibers. The dry unit weight of all specimens decreased with increasing rubber content, which can be explained by the low specific gravity of rubber particles. Water absorption decreased slightly with the increase in rubber particles size. These composite materials containing 10% Portland cement, 70% and 60% fly ash and 20% and 30% tire rubber particles have sufficient strength for masonry applications.

1. Introduction

Large quantities of industrial by-products are produced every year in Turkey, and a significant portion of these by-products continues to be landfilled as solid waste. Fly ash is a major solid industrial by-product created by combustion of pulverized coal in thermal power plants. The annual fly ash production is about 18 million tons in Turkey. Relatively, little of this by-product is currently utilized, and handling of vast quantities of this waste material is causing serious environmental problems. Utilization of fly ash as a by-product in the construction industry reduces technical and environmental problems. Many attempts have been made to demonstrate the use of high volumes of fly ash in the manufacture of structural and high-strength concrete systems. The use of concrete containing high volumes of fly ash has recently gained popularity as a resource-efficient, durable and sustainable option for a variety of concrete applications (Crouch et al., 2007). Naik and Chun (2003) have studied the effects of incorporating high volumes of class C fly ash on the properties of fresh and hardened concrete. They have indicated that superplasticized high-strength concrete using class C fly ash can be proportioned for 28-day strength levels of 100 MPa or more. The engineering properties of high performance, high volume fly ash concrete incorporating small quantity of silica fume have also been reported. The mixtures gave a compressive strength of 30–40 MPa at 28 days (Swamy and Hung, 1998). The most common use of fly ash is in the cement industry. In general, fly ash reduces the water consumption of cement, increases the setting times, reduces the heat of hydration and adds long-term strength to cement products. Bilodeau and Malhotra (2000) have advocated the use of high volumes of fly ash and other supplementary cementing materials in construction in order to reduce CO_2 emissions and other environmental considerations. Fly ash is used as cement extender or filler in the manufacture of building materials such as panels and boards (Yazici, 2007).

Waste tires are another major environmental problem, with an increasing volume of rubber waste in landfills from the disposal of used tires. The reuse of rubber tires remaining from the retreading process can minimize environmental impacts and help the natural resources. Many researchers have investigated the use of recycled tires mostly relating to applications such as asphalt pavement, waterproofing systems, and membrane liners. (Siddique and Naik, 2004; Cao, 2007).

Another approach to waste tires disposal is to incorporate the rubber wastes into cement-based materials. The literature on the use of tire rubber particles in cement-based materials generally focuses on using tire rubber particles as coarse or fine aggregate in concrete. Results indicate that the rubberized concrete mixtures possess lower density, increased toughness and ductility, lower

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compressive and tensile strength and more efficient sound insulation (Siddique et al., 2007). It has also been reported that mortars incorporating rubber shreds achieved workability comparable to or better than a control mortar without rubber particles (Raghavan et al., 1998). Because of the low specific gravity of rubber particles, the unit weight of the mixture containing rubber decreases with the increase in the rubber content. They also observed that rubber shreds incorporated into mortar help reduce plastic shrinkage cracking in comparison to control mortar. Eldin and Senouci (1993) studied the mechanical behavior of concrete containing rubber tires and showed that the concrete mixtures exhibited lower mechanical strengths but demonstrated a ductile and plastic failure. Moreover, the effect of the rubber particle size on the mechanical properties of concrete has been studied by Topcu (1995), and he observed that despite a decrease in both unit weight and compressive strength, elastic behavior improved. The addition of silica fume into the matrix improved the mechanical properties of the rubberized concretes and diminished the rate of strength loss (Güneyisi et al., 2004). Marzouk et al. (2007) investigated the effect of adding rubber to concrete mixes on freezing and thawing resistance. They concluded that concrete with crumb rubber performed better under freeze-thaw conditions than plain concrete. Hernandez-Olivares and Baluenga (2004) reported that the addition of crumb tire rubber to high-strength concrete slabs improved fire resistance and reduced the damage by fire.

Segre and Joekes (2000) worked on the use of tire rubber particles as an additive to cement paste. They concluded that the low-cost procedure and agents might be used for pretreatment of the surface of powdered tire rubber to increase its adhesion to cement paste. It has been reported that the deformation of modulus of cement-based mortar can be controlled by the proportion of rubber aggregate replacing natural sand. The incorporation of rubber aggregates obtained from shredded tires in cement-based mortars may be a suitable solution to limit their propensity for cracking. The rubberized mortars exhibit an enhanced strain capacity and increased free shrinkage (Turatsinze et al., 2005, 2007). Pierce and Blackwell (2003) suggested that crumb rubber is an ideal aggregate for controlled low-strength material, because of the reduction in end-product density and strength. Pinto et al. (2003) studied the mechanical properties of rubber powder that was added to Portland cement, and they concluded that concrete containing rubber powder has potential use in the manufacturing of solid blocks in the construction industry.

There is limited amount of research on rubberized cementitious products in construction applications such as concrete barriers, concrete blocks and rubber-added bricks. Some researchers have suggested that because of its light unit weight, rubberized concrete may also be suitable for architectural applications and as a secondary structural component (Fattuhi and Clark, 1996; Yang et al., 2001; Sukontasukkul and Chaikaew, 2006).

Recycling waste rubber, in particular discarded automobile tires, has become an increasingly important issue since this material has been banned from landfills. As a consequence of this ban and the lack of an alternative technology to dispose of large quantities of used tires, there are millions of used tires stockpiled, some illegally. Tire rubber has been successfully used in a number of civil engineering applications. Previous studies on leachate derived from crumb rubber showed no deleterious effects to the environment (Liu et al., 1998; Lisi et al., 2004). A prior research also showed that scrap tire rubber can absorb and retain volatile organic compounds. If tire chips are used in areas where contamination levels are high, they can be used as a sorbent for environmental clean up (Park et al., 2003). The acceptable limits for metals and organics in leachate from shredded tires are discussed in ASTM D 6270-98 (1998), which provides guidelines for using scrap tires in civil engineering applications.

Recycling waste materials such as tire rubber wastes and fly ashes, produced in an industrial process, conserve valuable natural resources and reduces the amount of waste entering landfills. The main method of recycling these waste materials is the manufacture of building materials or products. The aim of this study is to evaluate the feasibility of utilizing two wastes: fly ash and tire rubber particles, with Portland cement as construction materials.

2. Experimental study

Fly ash (FA) was obtained from Soma Seas Thermal Power Plant in Manisa, Turkey. The FA was produced from lignite coal, and contains significant amount of CaO with a lime content of 15.34%. The chemical composition of the FA is given in Table 1. According to ASTM C 618 (2005), the FA can be classified as a class C fly ash due to its chemical composition. In addition to having pozzolanic properties, this type of fly ash also has some cementitious properties. The total amount of SiO_2, Al_2O_3 and Fe_2O_3 is 74.32%, which is an amount larger than the value given by the ASTM standard for type C class FA. The free lime content of the FA complies with TSI (TS EN 450-1, 2006) and EN (EN 450, 1994) standards because it is 1.90%. The amount of SO_3 with 0.99% is less than the value given by the standards. Pozzolanic activity index (PAI) of the FA is 88% at 28 days, and this value satisfies the ASTM C 618 limit (75%). PAI also meets the TSI and EN criteria that are 75% and 85% at 28 days and 90 days, respectively. The amount of FA retained on a 45-mm sieve was 16%, which was less than 40% given in standards. Analysis of leachate from the FA was conducted by Baba and Kaya (2004) and they classified the fly ash samples as "non-toxic" waste based on CEN results. According to Cokca and Yilmaz (2004), the atomic absorption test results indicated that the concentration of all metals is below the stated EPA limits. This means that the leachates from Soma FA are not dangerous and hazardous.

The cement used in the study was ordinary Portland cement (PC) CEM I 42.5 produced according to TS EN 197-1 (2002). The specific gravity and specific surface area of the cement were 3.15 and 3516 $cm^2 g^{-1}$, respectively. The percentage of cement retained on a 40 μm sieve was 13.6%. Physical, chemical and mechanical properties of the Portland cement and fly ash are given in Table 1.

Rubber waste (RW) particles used in the research were obtained from mechanical shredding of waste automobile tires. Three size fractions of rubber waste were used: 0.0–0.25, 0.25–0.50 and 0.50–1.0 mm. Fig. 1 shows the three different size fractions of rubber waste.

The mixture containing Portland cement (PC), fly ash (FA) and rubber waste (RW) particles was based on dry weight percentages of the total mixture. The mix design was divided into two groups. In the first group (Group-I), FA and RW contents were 60% and 30%, respectively. In the second group (Group-II), FA and RW contents were 70% and 20%, respectively. The amount of PC was 10% by dry weight of the total mixtures for both group mixes. A control mix was prepared by mixing 10% PC and 90% FA with water. The water content for each mix was determined by a flow test obtaining a flow within 110–115 mm. The mixture design and the water-to-binder ratio (W/B) of the mortar mixes are given in Table 2. The water was regular tap water. The tire rubber particles, Portland cement and fly ash were initially dry-mixed in a Hobart mixer, and then water was added. The mixtures were cast in two layers into three-gang molds compacting by a vibration table for 60 s. After casting, all specimens were stored in a moisture room for 24 h at a relative humidity of 65% at 20 °C. After demolding, the specimens were cured in water at 20 °C until the time of testing.

The flexural and compressive strength tests were performed at 14, 28 and 56 days in conformance with TS EN 196-1 (2002). For the flexural strength test, three specimens from each mixture were

Table 1
Physical, chemical and mechanical properties of PC and FA.

Chemical composition (%)	PC	FA	Physical properties of Portland cement	
SiO_2	20.04	56.26	Specific gravity	3.15
Al_2O_3	5.81	28.54	Initial setting time (min)	150
Fe_2O_3	3.62	5.42	Final setting time (min)	185
CaO	61.52	4.54	Volume expansion (mm)	2.00
MgO	1.43	1.37	Specific surface (cm^2/g)	3516
Na_2O	0.18	0.15	Compressive strength (MPa)	
K_2O	0.94	1.74	2 days	22.0
SO_3	2.87	0.28	7 days	38.7
Free CaO (%)	1.41	–	28 days	46.8
Cl^-	0.013	–	Specific surface of FA (cm^2/g)	3794
LOI	2.60	1.35	Specific gravity of FA	1.95

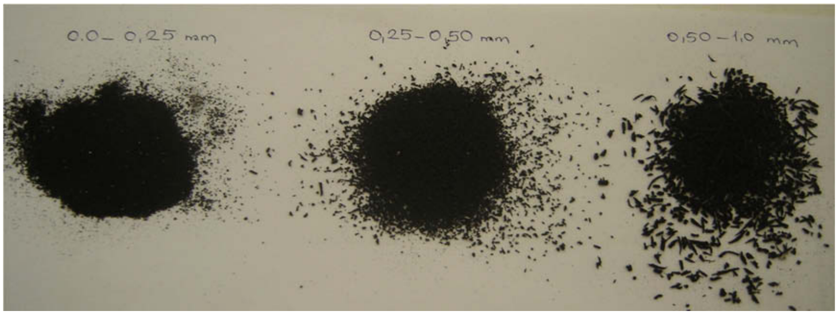

Fig. 1. Rubber waste particles used in the experimental study.

prepared and tested by one-point loading configuration with a span of 10 cm. The flexural strength test was performed using an ELE model testing machine with a capacity of 10 kN. Compressive strength tests were performed using six broken pieces of test prisms left from the flexural strength test. Compressive strength measurements were carried out using an ELE International ADR 3000 hydraulic press with a capacity of 3000 kN; the loading rate was 0.25 $N/mm^2/s$. The evaluation of the water absorption for 24 h in water and unit weight was performed on cubes of 5 cm. The specimens aged 28 days were dried in an oven at 50 °C and then allowed to cool to room temperature. For the determination of water absorption by total immersion, the dry mass for each specimen was recorded and then totally immersed in water at 20 °C until it achieved a constant mass. The gain in weight, expressed as a percentage of the dry weight, was of the water absorption of the specimens.

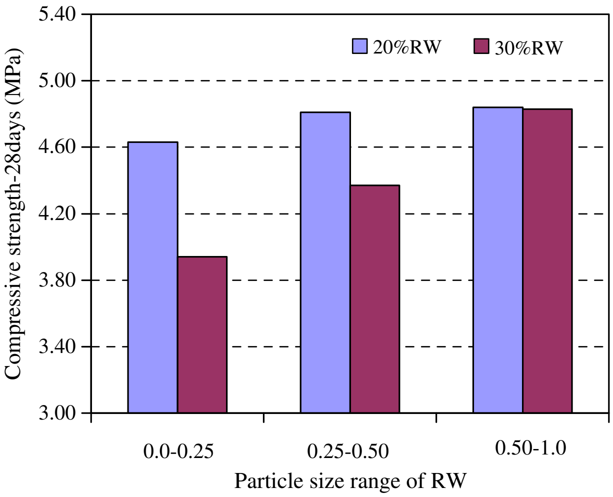

Fig. 2. Compressive strength (28 days) of the mixtures versus rubber waste content.

3. Test results and discussions

The 28-day compressive strength as a function of percentage of rubber for different rubber fractions is presented in Fig. 2. The test results indicated that there was a reduction in the compressive strength with the increase in rubber content compared to the control mix. The compressive strength of the control mix was evaluated as 5.82 and 7.11 MPa at 14 and 28 days, respectively. The reductions in compressive strength (28 days) were 15%, 9% and 0.2% for 0.0–0.25, 0.25–0.50 and 0.50–1.0 mm fractions, respectively, with an increase in rubber content from 20% to 30%. This trend is slightly influenced by the size fraction of the RW. Comparisons between three rubber fraction sizes indicate that the rubber particles with 0.50–1.0 mm diameter seemed to have a better compressive strength than the others. However, no significant difference in compressive strength was observed between the 20% and 30% content of the mixtures containing RW 0.50–1.0 mm in diameter. For a given amount of rubber, fine particles lead to great losses in compressive strength compared to the other particles, especially at the 30% rubber content. The mixtures with a 20% RW percentage present the maximum compressive strength, 4.84 MPa at 28 days for rubber particles with a diameter of 0.50–1.00 mm. Previous studies also indicated that the reduction for compressive strength of rubberized concrete was observed with the use of higher rubber content. The results of various studies also indicated that the size, proportions and surface textures of rubber particles noticeably affect the compressive strength of rubberized concrete mixtures (Eldin and Senouci, 1993; Topcu, 1995). The reduction in compressive strength is attributed to the physical properties of the rubber particles, since they are less stiff than the cement paste. Also the decrease in the strength might be due to a poor bond between the cement paste and the rubber particles. The compressive strength gain of the mixtures with time can be seen in Fig. 3. The rate of compressive strength development is relatively high between 14 and 28 days, followed by a slower rate between 28 and 56 days.

The variation in 28-day flexural strength as a function of rubber content for different size particles is shown in Fig. 4, and all results are presented in Table 3. Flexural strength of control mix was evaluated as 0.51 and 0.73 MPa at 14 and 28 days, respectively. For flexural strength, the specimens with RW showed higher values than the control mix probably due to the effect of rubber fibers. The mixtures with a 20% RWe content present the maximum flexural strength of 1.40 MPa at 28 days for particles 0.50–1.0 mm in diameter, compared to the control mix. There is a reduction in flexural strength (28 days) with an increase in rubber content. These reductions were 1%, 10% and 21% for 0.0–0.25, 0.25–0.50 and 0.50–1.0 mm fractions, respectively, with an increase in RW content from 20% to 30%. This is possibly due to the reduction of binder content in the mixtures. Fig. 5 shows the development of flexural strength with curing period (14, 28 and 56 days) for the mixtures containing 20% RW, 70% FA and 10% PC. Results also indicated that for a given rubber content, flexural strength increases with curing time.

Fig. 6 shows the fracture surfaces of specimens submitted to bending stress after failure. The failure of specimens containing RW did not exhibit the typical brittle type failure normally obtained for conventional cement-based materials during compression or tension test (Fig. 6a, b and c). It has been observed that the control specimens (Fig. 6d) split into two pieces immediately after cracking, while the specimens containing rubber particles showed a larger deformation without complete disintegration. Although there were large cracks, the rubber fibers held the specimen as one piece. The control specimens containing a high per-

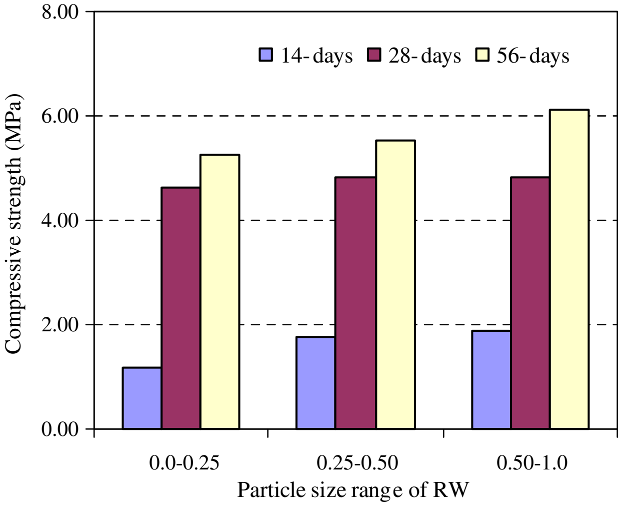

Fig. 3. Compressive strength of the mixtures containing 20% RW versus curing time.

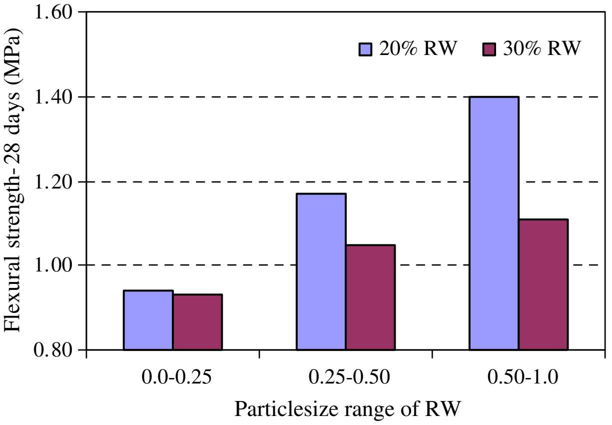

Fig. 4. Flexural strength (28 days) of the mixtures versus rubber waste content.

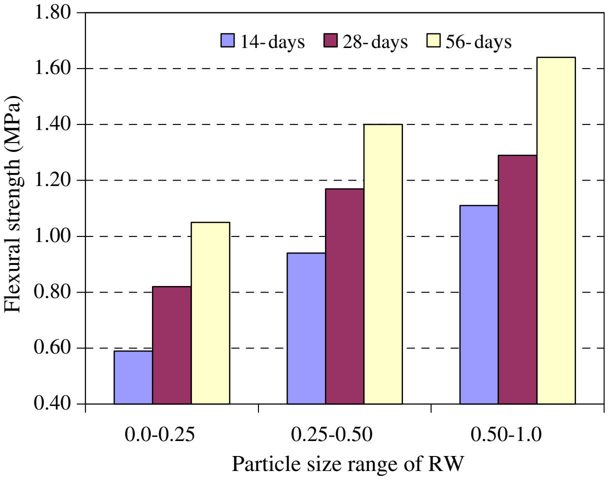

Fig. 5. Flexural strength of the mixtures containing 20% RW versus curing time.

Table 2
Mix proportions and some properties of the mixtures.

Mix	RW particle fractions (mm)	RW (%)	PC (%)	FA (%)	W/B W/(PC+FA)	Dry unit weight (Kg/m^3)	Water absorption (%)	Compressive strength- 28 days (MPa)	Flexural strength-28 days (MPa)
Group-I	0–0.25	20	10	70	0.55	1078	30	4.63	0.94
	0.25–0.50				0.50	1192	26	4.81	1.17
	0.50–1.0				0.46	1200	24	4.84	1.40
Group-II	0–0.25	30	10	60	0.63	1011	29	3.94	0.93
	0.25–0.50				0.57	1096	27	4.37	1.05
	0.50–1.0				0.52	1144	25	4.83	1.11

Table 3
Mechanical properties of the mixtures containing 20% RW.

RW (%)	Fraction size (mm)	Compressive strength (MPa)			Flexural strength (MPa)		
		14 days	28 days	56 days	14 days	28 days	56 days
	0–0.25	1.19	4.63	5.24	0.59	0.94	1.11
20	0.25–0.50	1.75	4.81	5.52	0.82	1.17	1.29
	0.50–1.0	1.89	4.84	6.11	1.05	1.40	1.64

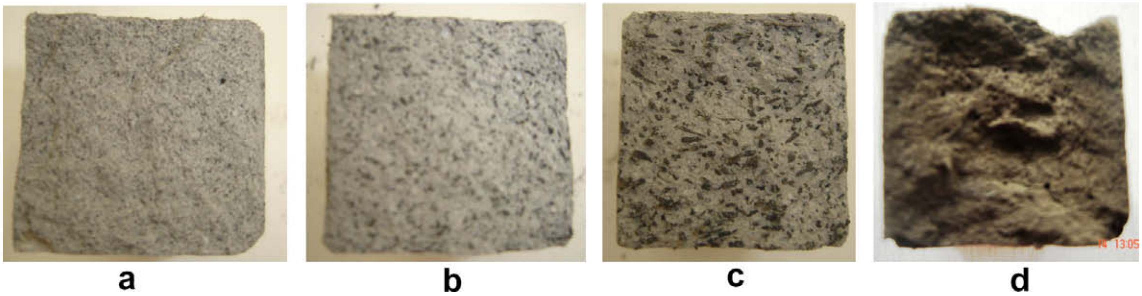

Fig. 6. Fracture surfaces of specimens with rubber particles (0–0.25 mm (a), 0.25–0.50 mm (b) and 0.50–1.0 mm (c), in diameter) and specimen without rubber particles (d) submitted to bending stress after failure.

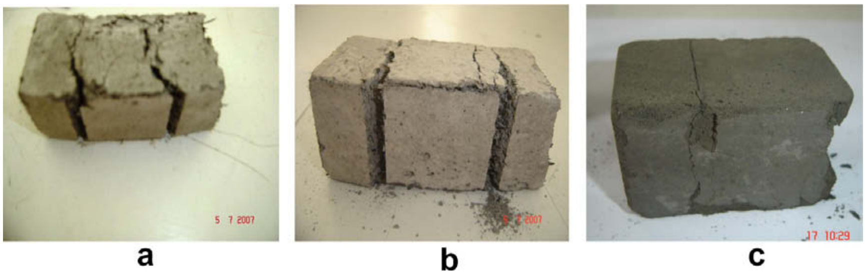

Fig. 7. The specimens containing rubber particles (a and b) and control specimen (c) after compression test.

centage of FA (90%) showed early cracks because of their weakness against tension. Fig. 7 also shows the specimens after compression test. Results of various studies showed that as the rubber content is increased, the specimens tend to fail gradually (Eldin and Senouci, 1993; Khatib and Bayomy, 1999).

The variation in dry unit weight versus rubber content and particle fractions is presented in Table 2. Because of the low specific gravity of rubber particles, the dry unit weight of the mixtures decreases with the increase in the percentage of RW. Moreover, increase in RW content increases the air content which in turn reduces the dry unit weight of the specimens (Khatib and Bayomy, 1999). The dry unit weight changed between 1078 and 1200 kg/m^3 for the mixtures containing 20% rubber particles. The dry unit weight also changed between 1011 and 1144 kg/m^3 for the mixtures containing 30% rubber particles. Water absorption values of the mixtures are shown in Table 2. Water absorption decreased slightly with the increase in the size of the rubber particles. For the 0.25–0.50 and 0.50–1.0 mm particle sizes, the water absorption increased with the increase in the RW content. The incorporation of rubber particles in cementitious matrix tends to restrict the water absorption of the composite (Fattuhi and Clark, 1996). According to Segre and Joekes (2000), the addition of rubber particles lowers the amount of water absorbed, since the rubber particles do not absorb water. The water requirements for a constant flow of 110 ± 5% for mortar are also shown in Table 2. It can be seen that the increase in RW content increased the water-to-binder ratio (W/B). The fineness of the rubber particles affects the water demand of the mixtures. It was also observed that the mixtures made with fine rubber particles require more water. However, the increase in FA content decreases water requirements. The reduction in water requirement was due to the spherical shape and the smooth surface of FA, which helped the flow and workability of the mixture.

The investigated composite materials having a maximum 4.84 MPa of compressive strength can be used in masonry applications. The average and minimum compressive strength of clay masonry units prescribed in Turkish standards are 5.0 and 4.0 MPa, respectively (TS EN 771-1, 2005). In the relevant European Standards (EN-771-1, 2003; EN-771-2, 2003), the minimum mean values of compressive strength of masonry units are minimum 2.5 MPa for clay units and 5.0 MPa for calcium silicate units. These composite materials containing 10% Portland cement, 70% and 60% fly ash and 20% and 30% tire rubber particles have sufficient strength for masonry applications.

4. Conclusions

The study investigated the possibility of using fly ash and rubber waste with Portland cement as construction material. Based on the study following conclusions may be drawn:

- The compressive strength of the mixtures decreased with the increase of rubber waste particles for all curing periods tested (14, 28 and 56 days). However, the strength of the mixtures increased with an increasing fly ash content. Compressive strength is slightly influenced by the particles size. The mixtures with a 20% rubber waste content present the maximum compressive strength, 4.84 MPa at 28 days.
- The specimens with waste tire rubber showed higher flexural strength values than the control mix, probably due to the effect of rubber fibers. The increase in rubber waste content from 20% to 30% decreases the flexural strength of the mixtures. This decrease is lower as the size of tire rubber particles decreases.
- The increase in rubber waste content decreased the dry unit weight. This is because of the low specific gravity of rubber compared to the fly ash it replaces.
- Water absorption decreased slightly with the increase in the size of the rubber particles. For the 0.25–0.50 and 0.50–1.0 mm size fractions, the water absorption increased with the increase in the rubber content.
- The increase in rubber waste content increased the water-to-binder ratio. However, the increase in fly ash content decreases the water requirement of the mixture. Also, the fineness of rubber waste particles influences the water requirements for the preparation of the mixtures.

- For economic and strength requirements, the fly ash content should be kept as high as possible.

One of the main areas to utilize fly ash and rubber tire wastes is in manufacturing composite materials for masonry applications. Utilization of these wastes in the construction industry in large quantities seems to be a reasonable solution for these environmental and economic problems. Finally, the use of rubber tire waste and fly ash in composite materials provides an opportunity to recycle these wastes and thus to achieve an environmental goal.

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