revealed the highest compressive strength and hardness values, together with a moderate flexural strength that remains higher than the requirements for clay and industrial floor bricks. Therefore, this mix will be the main focus for the further service properties evaluation.

4.3 Service Properties

4.3.1 Abrasion Resistance

To evaluate the wear resistance of the recycled plastic waste composite material, abrasion tests were conducted on the group of samples prepared at 240°C using sieve 2 with different sand contents. The results are shown in Table 4.7. The average loss in thickness ranged from 0.05-0.24 mm. Mix 10 (20% sand, sieve 2 and temperature 240°C) revealed the highest abrasion resistance value and this value decreased with increasing the sand content as shown in Figure 4.15.

Table 4.7: Abrasion Resistance Results of Prepared Mixes

Mix No.	Sample No.	Weight Before Abrasion, (g)	Weight After Abrasion, (g)	Bulk Density, (g/cm^3)	Thickness Loss, (mm)	Average Thickness loss, (mm)
Mix 10	1	128	127	1.08	0.19	0.05
	2	164	164	1.08	0	
	3	156	156	1.08	0	
	4	122	122	1.08	0	
Mix 11	1	243	243	1.06	0	0.1
	2	183	182	1.06	0.2	
	3	177	176	1.06	0.19	
	4	179	179	1.06	0	
Mix 12	1	205	203	1.08	0.37	0.24
	2	196	195	1.08	0.19	
	3	209	208	1.08	0.19	
	4	217	216	1.08	0.19	

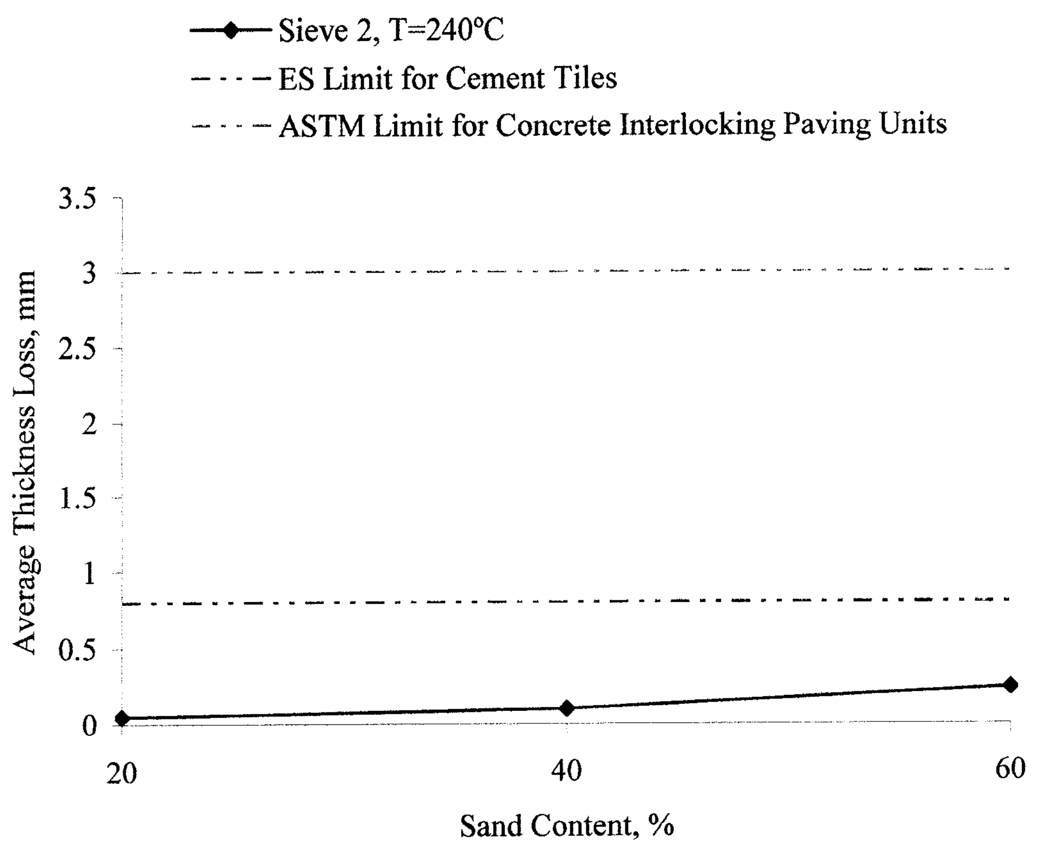

Figure 4.15: Variation of Average Thickness Loss with Sand Content

Abrasive wear is the natural consequence of the shearing of junctions between surfaces caused by the introduction of abrasive particles from outside; by using soft plastics, the abrasive particles will sink below the surface resulting in no further harm.(56) Thus, increasing the polymeric content on behalf of the filler reduces abrasive wear and seizure can be completely avoided. Moreover, when there is a weak adhesive bond between the filler and the polymeric matrix; fillers will increase the rate of wear of the material due to the ease by which the filler gets separated from the matrix. Hence, increasing the sand content will decrease the resistance to abrasion.

Regardless of the differences encountered in the average thickness loss between the mixes, the highest value of 0.24 mm for mix 12 (60% sand, sieve 2 and temperature 240°C) was 70% lower than the Egyptian standard limit for cement tiles, and 92% lower than the ASTM standard limit for solid concrete interlocking paving units. Hence, all mixes reveal an excellent abrasion resistance.

4.3.2 Density and Water Absorption

The density and water absorption results of the different mixes investigated are shown in Table 4.8, while the average values are listed in Table 4.9. All mixes resulted in low densities ranging between 1.12-1.68 g/cm^3. Mix 3 (60% sand, sieve 1 and temperature 185°C), mix 6 (60% sand, sieve 2 and temperature 185°C), mix 9 (60% sand, sieve 1 and temperature 240°C) and mix 12 (60% sand, sieve 2 and temperature 240°C) had the highest density values ranging from 1.59-1.68 g/cm^3, while the lowest density values ranging from 1.12-1.16 g/cm^3 correspond to mix 1 (20% sand, sieve 1 and temperature 185°C), mix 4 (20% sand, sieve 2 and temperature 185°C), mix 7 (20% sand, sieve 1 and temperature 240°C) and mix 9 (20% sand, sieve 2 and temperature 240°C). Moreover, mixes 2 (40% sand, sieve 1 and temperature 185°C), mix 5 (40% sand, sieve 2 and temperature 185°C), mix 8 (40% sand, sieve 1 and temperature 240°C) and mix 11 (40% sand, sieve 2 and temperature 240°C) possessed intermediate density values ranging between 1.27-1.41 g/cm^3. The increase in density with the sand content returns to the high density of sand compared to polymeric material. Figure 4.16 shows the variation of density with the mixing temperature for the different sand contents. It is evident from the figure that the higher the mixing temperature the denser the material. This indicates a better adhesion between the sand particles and the polymeric matrix with the increase in mixing temperature as a result of the less pores and voids present in the structure, which agrees with the observation made earlier in the optical micrographs (Figures 4.1 and 4.2).

Table 4.8: Densities and Water Absorption Results of Prepared Mixes

Mix No.	Sample No.	Density (g/cm^3)	Conditioned Weight (g)	Wet Weight (g)	Water Absorption (%)
Mix 1	1	1.18	46.86	47.49	1.34
	2	1.09	41.90	42.62	1.72
	3	1.08	29.79	30.31	1.75
Mix 2	1	1.32	52.89	53.24	0.66
	2	1.15	52.68	53.06	0.72
	3	1.34	39.52	39.81	0.73
Mix 3	1	1.69	45.75	46.23	1.05
	2	1.56	72.53	73.85	1.82
	3	1.64	57.39	58.34	1.66
Mix 4	1	1.08	30.34	30.53	0.63
	2	1.16	48.01	48.43	0.87
	3	1.14	40.06	40.3	0.60
Mix 5	1	1.37	46.10	46.59	1.06
	2	1.18	51.41	51.77	0.70
	3	1.33	34.74	35.11	1.07
Mix 6	1	1.57	58.63	59.14	0.87
	2	1.59	43.30	44.01	1.64
	3	1.62	53.54	53.96	0.78
Mix 7	1	1.11	30.47	31.06	1.94
	2	1.16	33.53	33.76	0.69
	3	1.09	35.10	35.27	0.48
Mix 8	1	1.34	37.25	37.48	0.62
	2	1.39	37.95	38.2	0.66
	3	1.45	53.86	54.2	0.63
Mix 9	1	1.6	66.79	97.82	1.54
	2	1.62	69.41	70.36	1.37
	3	1.55	60.78	61.37	0.97
Mix 10	1	1.2	37.91	38.19	0.74
	2	1.11	29.87	30.25	1.27
	3	1.18	37.32	37.67	0.94
Mix 11	1	1.41	38.07	38.41	0.89
	2	1.41	35.25	35.53	0.79
	3	1.4	35.40	35.68	0.79
Mix 12	1	1.61	42.96	43.53	1.33
	2	1.73	60.06	60.49	0.72
	3	1.69	59.99	60.3	0.52

Table 4.9: Average Densities and Water Absorption Results of Prepared Mixes

Mix No.	Density (g/cm^3)	Water Absorption (%)
Mix 1	1.12	1.6
Mix 2	1.27	0.71
Mix 3	1.63	1.51
Mix 4	1.13	0.7
Mix 5	1.29	0.94
Mix 6	1.59	1.1
Mix 7	1.12	1.04
Mix 8	1.39	0.64
Mix 9	1.59	1.29
Mix 10	1.16	0.98
Mix 11	1.41	0.83
Mix 12	1.68	0.85

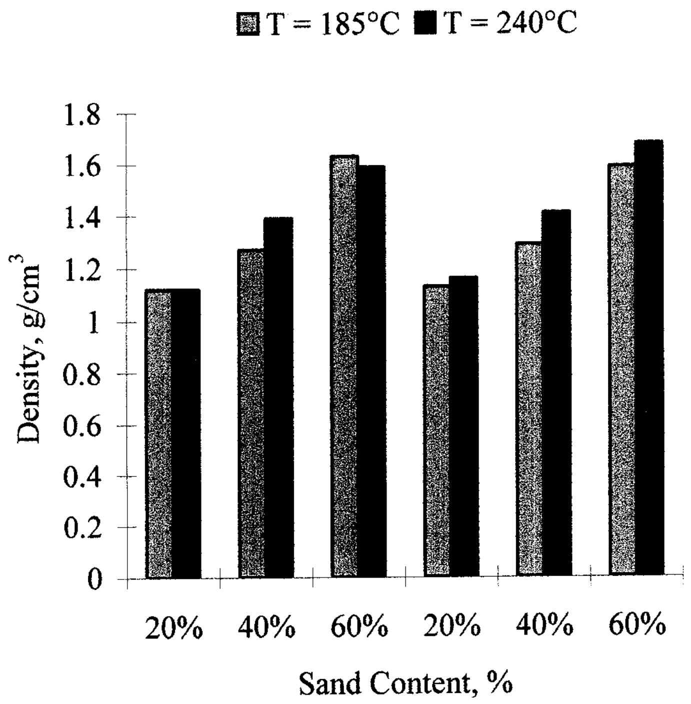

Figure 4.16: Effect of Mixing Temperature on the Density of the Prepared Mixes

Table 4.10 lists the maximum water absorption percentages entitled by the ASTM and the Egyptian standards for various types of bricks, tiles and paving units, compared to those produced by the composite material. It is evident from the table that even mix 1 (20% sand, sieve 1 and temperature 185°C) holding the highest average water absorption value over all the investigated mixes of 1.6% easily satisfies all the standard requirements for industrial floor bricks, interlocks, paving bricks and cement tiles.

Table 4.10: Maximum Water Absorption Percentages for Construction Bricks and Tiles

Application	Standard Specification	Water Absorption (%)
Industrial Floor Brick	ASTM C410-60	1.5-12%
Solid Concrete Interlocking Paving Units	ASTM C936-96	5%
Pedestrian and Light Traffic Paving Brick	ASTM C902-95	11-17%
Cement Tiles	ES 269-1974	12%
Recycled Plastic Waste Composite Material		0.64-1.6%

It is evident from Table 4.10 that the investigated plastic waste composite reveals superior water absorption resistance when compared to cementitious materials. However, the values are slightly higher than those expected for most plastics (less than 1% absorption). This could be related to the presence of imperfections in the prepared specimens, either in the form of cavities, minor waste constituents such as paper or pores resulting from the use of sand as filler material.

4.3.3 Resistance to Chemical Reagents

In order to evaluate the chemical resistance of the recycled plastic waste composite, samples from mix 12 (60% sand, sieve 2 and temperature 240°C) revealing the highest compressive strength and hardness values were immersed in three reagents, sodium hydroxide solution (10%), sulfuric acid (3%) and benzene. Tables 4.11-4.13 list the average increase in weight over an immersion period of four weeks for the three reagents. It is apparent from the results that the material posses excellent chemical resistance to acids and alkalis. The average increase in weight after 28 days was 1.37% and 3.38% for the sulfuric acid and the sodium hydroxide solution, respectively. However, the increase in weight after seven days was nearly half the values for the total immersion time. On the other hand, the increase in weight associated with the benzene reagent was much higher starting at a 5.59% increase after the first seven days and reaching 9.85% after 28 days. It is well known that most polymers exhibit very high resistance to chemical attacks by acids and alkalis. However, they are less resistive to organic solvents which react with the carbon atom chains and their pending side groups. This explains the increase in absorption rates for the benzene reagent. A visual analysis was also performed on the samples and revealed no evidence of decomposition, discoloration, swelling or cracking for the total immersion time.

Table 4.11: Chemical Resistance of Samples Subjected to 10% Sodium Hydroxide Solution

Mix No.	Sample No.	Weight (g)				Increase in Weight (%)		
		Initial	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
12	1	39.08	39.66	39.93	40.14	1.48	2.18	2.71
	2	33.99	34.75	35.05	35.26	2.24	3.12	3.74
	3	37.32	38.11	38.38	38.7	2.15	2.84	3.7
	Average Increase in Weight, %					1.95	2.71	3.38

Table 4.12: Chemical Resistance of Samples Subjected to 3% Sulfuric Acid

Mix No.	Sample No.	Weight (g)				Increase in Weight (%)		
		Initial	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
12	1	30.34	30.58	30.73	30.74	0.79	1.29	1.32
	2	40.05	40.37	40.52	40.62	0.8	1.17	1.42
	3	37.9	38.22	38.4	38.42	0.84	1.32	1.37
	Average Increase in Weight, %					0.81	1.26	1.37

Table 4.13: Chemical Resistance of Samples Subjected to Benzene

Mix No.	Sample No.	Weight (g)				Increase in Weight (%)		
		Initial	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
12	1	30.46	32.37	33.48	34.06	6.27	9.91	11.81
	2	33.5	34.66	35.28	35.81	3.46	5.31	6.9
	3	32.83	35.14	36	36.39	7.04	9.66	10.84
	Average Increase in Weight, %					5.59	8.29	9.85

4.3.4 Vicat Softening Temperature

In order to evaluate the thermal resistance of the recycled plastic waste composite when exposed to outdoor environments. The Vicat softening temperature test was performed on three samples from the optimum mix 12. The results indicated a softening temperature between 93-110°C which is much higher than the expected service temperature of 60°C. This variation between the softening temperatures may be attributed to the inhomogeneous phases present in the material that appear only on the micro level as sown in Figure 4.1 (b) and (c).

4.4 Environmental Related Tests

4.4.1 Health Hazards of the Investigated Waste Material

In order to assess any harmful effects that could be associated with the utilization of solid waste rejects in the preparation of a composite material, tests were performed to determine the heavy metals content by water leaching according to DIN 3814-S_4 on samples with different sand concentrations and prepared at different mixing temperatures. Table 4.14 lists the results of the leaching tests by water for 28 days together with the World Health Organization (WHO) guideline values[46] for heavy metal content in drinking water.

The results shown in Table 4.14 indicate very low concentrations of heavy metals for the various mixes. It is obvious that the samples are nearly free from any cadmium (Cd); contain very small amounts of lead (Pb) and chromium (Cr). The only exception was mix 12 that revealed high concentrations of 2.2 μg/L and 3.2 μg/L, for lead and chromium respectively. Nevertheless, all mixes showed concentrations far below the WHO guideline values which proves the health safeness of the use of the recycled plastic waste composite material.

Table 4.14: Heavy Metal Content by Water Leaching for 28 Days

Mix No.	Element Concentration (μg/L)		
	Lead, Pb	Chromium, Cr	Cadmium, Cd
Mix 4	0.1	0.2	0
Mix 5	1.4	1.5	0
Mix 6	0	0	0
Mix 10	0.4	0	0
Mix 11	0.1	0	0
Mix 12	2.2	3.2	0.1
Blank Sample	0.2	0.8	0
WHO Guidelines	10	50	3

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS

5.1 Major Study Findings

Based on the results of the experimental study presented in chapter four regarding the proposed utilization of municipal solid waste rejects in the production of a recycled plastic waste composite material with the potential for use in construction applications, the following conclusions can be drawn:

- The morphological analysis of the composite material reveals a general intact structure with the presence of polymer segregation phases and particle filler (sand) clustering phases. The tendency of polymer segregation decreases with increasing temperature and decreasing sand concentrations. Clustering of sand particles depends on the concentration of the filler employed as well as its size; the clustering tendency increases with increasing the filler concentration and with decreasing the particle size.

- The composite material with fine sand particles displays a stress-strain behavior of an elastomeric material for both mixing temperatures and for sand concentrations of 20% and 40%. Composites with higher sand concentrations display a ductile crystalline polymer behavior.

- The composite material with coarser sand particle size displays a stress-strain behavior of a ductile crystalline polymer for both mixing temperatures and all sand concentrations.

- Increasing the sand content in the composite material results in increasing the compressive strength, a similar effect occurs with increasing the sand particle size and the mixing temperature.

- Composite material with 60% sand content, sieve 2 and mixing temperature 240°C displays 7.25% higher compressive strength than the ASTM limit for pedestrian and light traffic paving bricks.

- For all investigated mixes, the composite material has modulli of rupture higher than clay bricks and the ASTM limits for industrial floor bricks.

- The flexural strength of the composite material increases with the increase in mixing temperature, and decreases with increasing sand content at low mixing temperature, while a reverse effect occurs at high mixing temperature for the 20% and 40% sand content. Sand content higher than 40% results in a decrease in flexural strength.

- For all investigated mixes, the hardness values of the composite material demonstrate weak scratch resistance capability and place it within the moderately hard plastics range.

- Increasing the sand content in the composite material results in increasing the hardness, a similar effect occurs with increasing the sand particle size and the mixing temperature.

- The abrasion resistance of the composite material is 70% higher than the Egyptian standard limit for cement tiles and 92% higher than the ASTM limit for solid concrete interlocking paving units. Increasing the sand content in the composite material results in decreasing the abrasion resistance.

- The water absorption values for the composite material are much far below the ASTM standard limits for industrial floor bricks, pedestrian and light traffic paving bricks, solid concrete interlocking paving units and the Egyptian limits for cement tiles. The water absorption values are slightly higher than those of plastics.

- The composite material possesses excellent chemical resistance to acidic and alkaline environments and moderate resistance to organic solvents.

- The Vicat softening temperature of the composite material is much higher than the expected service temperature of the proposed application.

- All the leaching values are far below the WHO guidelines for drinking water. The composite material can be safely used for the proposed applications.

- The air quality test of the fumes evolving during the material production reveals excessive concentrations of CO. The values are much higher than the emission limits required by the EEAA.

- Based on the compressive strength, flexural strength and chemical resistance of the composite material, it can be used to manufacture paving bricks, large tiles or sheets for use in industrial facilities where physical requirements are not of great importance.

5.2 Recommendations

- Prior to the use of the composite material in practical applications, it is highly recommended to determine the fire behavior of the material by conducting ignition tests, smoke tests and fire toxicity tests.

- The compressive strength values of the composite material failed to meet the ASTM limit for solid concrete interlocking paving units, hence it is recommended to investigate the compressive strength associated with increasing the sand content beyond 60% and the mixing temperature beyond 240°C to try to meet the ASTM requirements.

- Several attempts were made to join bricks manufactured from the composite material using mortar. However, the bond strength was very weak and the bricks detached easily from each other. Therefore, in case of using the composite material for manufacturing structural bricks, it is important to search for a cheap and reliable joining method. Mechanical fixing seems a promising alternative where holes can be produced in the bricks to allow for further holding by studs.

- The major problem encountered during the manufacturing of the composite bricks was the extensive emissions from the mixer stack, which was analyzed and the results indicated very high concentrations of air pollutants resulting from the plastic heating process. Therefore, a study proposing the best air pollution control system should be carried out before the start of any mass production activities.

- During the sample brick production, several attempts were made to color the product using metal oxides. The results were promising and bricks maintained their colors without degradation for several weeks. It is recommended to investigate the effect of these pigments on the mechanical and service properties of the composite material.

- The composite material revealed very low water absorption values. Therefore, it is recommended to conduct further permeability tests in order to evaluate the potential use of the material as a liner. However, such application will entitle a reliable mean to join the produced sheets or tiles together. The use of dovetail interlocks seems a promising method.

- Extensive studies should be conducted on the resistance of the composite material to environmental attack. The studies should include the effect of ultraviolet radiation and microorganisms. In addition, tests for the leaching of organic compounds should be performed on the composite material.

- The stress-strain behavior of many filled polymers is known to be altered by the addition of adhesion promoters and silane coupling agents. These additives will change the nature of the filler polymer interface resulting in increased tensile strengths. Hence it is recommended to incorporate such fillers in the composite material to expand its structural ability.

- Water is a plasticizer for many polymers and can result in a decrease in the tensile strength and the elastic modulus. In addition, water swells the polymer creating stress concentrations. Therefore, it is important to investigate the mechanical properties of the composite material as a result of water absorption.

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