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Improving the Mechanical Properties of Recycled Asphalt Pavement Mixtures Using Steel Slag and Silica Fume as a Filler

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Abstract: Due to its environmental and economic advantages, the use of recycled materials in asphalt mixes is witnessing increased interest, where the properties of those mixes are significantly affected by the properties of the recycled materials in them. This paper discusses the results of an experimental study conducted to evaluate the performance of recycled asphalt mixtures made with reclaimed asphalt pavement aggregate (RAP). These mixtures were also prepared with two filler additives, namely steel slag (SS) and silica fume (SF), at four different percentages by weight of the aggregate. A total number of 234 mixtures were tested. The laboratory results indicated the effectiveness of using such additives as a filler material. The Marshall stability showed improvement for mixes prepared with steel slag ranging from 11.73 to 32.73 kN as the RAP level increased; the highest stability load was recorded for the 75% RAP with a 50% steel slag mix. On the other hand, the silica fume depicted variance in its strength, yet the maximum load value of 31.02 kN was for the 75% RAP with 100% silica fume. The use of steel slag in the presence of water decreased the stability results, while satisfying the ASTM standards.

Keywords: RAP; asphalt; Marshall; steel slag; silica fume; optimum asphalt content

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1. Introduction

The different properties of the different components of asphalt mixtures have direct implications on the properties of the mixture and their performance under the various traffic loading and climate conditions. The main components of hot-mix asphalts (HMA) are asphalt binder and mineral aggregates, which constitute 90–95% by weight and 75–85% by volume of the HMA [1]. Therefore, the properties of HMA are significantly affected by the physical and chemical properties of the aggregates in the mix. There have been many studies on the use of recycled materials as partial replacement of aggregates in HMA, where some studies have shown that utilizing 100% recycled aggregates can reduce the road construction cost by up to 70% [2]. Besides the benefits of using the HMA technology, including its simplicity and sustainability promotion in the pavement fields, there are some drawbacks such as the affordability compared with the cold-mix technology and the specified climate conditions (i.e., the outdoor temperature of at least 40 °C).

The reduction in virgin material (i.e., virgin binder and aggregate) production costs, natural resources conservation, and landfill space clearance are some of the benefits that recycled materials offer to the asphalt paving industry [3–7]. The use of reclaimed asphalt pavement (RAP) has been a common practice as it has shown promising results related to the asphalt mixture's performance characteristics, including cracking resistance, fatigue life, rutting resistance, and moisture susceptibility [8–14]. In particular, Mulatu et al. [15] studied the Marshall stability, rutting, and moisture susceptibility on a total of 64 mix designs. They investigated seven different replacement ratios up to 65%. The results showed that as the

RAP content in the hot asphalt mixtures increased, the tensile strength ratio decreased, while maintaining the limits of the standards and providing resistance to deformation and moisture-induced damage. They also concluded that replacing the crushed aggregate with 45% of RAP material satisfied the stability, flow, and volumetric properties' specification limits. Heating RAP material, as reported by Mallick et al. [16], showed its effectiveness in enhancing the binder dispersion, compatibility, and densification of the asphalt mixes, which, in turn, resulted in improving their strength, workability, and stiffness. Moreover, Gao et al. [17] stated that the duration of mixing showed its influence on the blending and dispersion of the hot asphalt mixes prepared with RAP. As the mixing duration increased, the performance of the recycled asphalt mixture improved; the optimum mixing times were 60s and 90s for the mixing plant and laboratory, respectively. Nowadays, researchers have used modifier or rejuvenating agents to enhance the asphalt pavement performance. One particular research is the study conducted by Malinowski et al. (2022) [18]. Four different modifiers were tested with and without a crosslinking agent. The results demonstrated the dual crosslinked biopolymer effect by the increase in the water and frost resistance by about 9%. In a different study, the rutting resistance and the fatigue life of the epoxy asphalt recycled mixture were evaluated [19]. It showed that the mixes with the epoxy asphalt recycled mixture were better in their rutting and cracking resistance. Additionally, they concluded that there was a potential to recycle a mixture with 100% RAP content.

Similar to RAP material, researchers have investigated the use of steel slag (SS) in the hot asphalt mixes and have evidenced their possibility of substituting the natural aggregate [20–24]. Steel slag is a byproduct waste material that comes from steel-making furnaces during the separation of the molten steel from the impurities [25,26]. Its properties depend on the process type of crude steel production, the valorization process, and the slag cooling conditions [27,28]. The steel slag application in road construction showed not only an improvement in the hot asphalt mixture performance but also proved to be an economical and environment-friendly option, because it minimizes the non-renewable natural aggregate's consumption in asphalt pavements every year and empties the occupied space of dumped waste in landfills [26–33].

In the literature, past studies have shown excellent results when substituting the natural aggregate of the hot asphalt mixtures with the coarse part of the steel slag in their rutting resistance, stability, tensile strength, and fatigue life [34–38]. In 2015, Zumrawi and Khalill [39] conducted their experimental tests on four different percentages of steel slag (e.g., 0%, 50%, 75%, and 100%). They concluded that replacing natural aggregate with steel slag at their optimum asphalt content increased the Marshall stability and density of the hot asphalt mixtures and decreased both air void ratios and flow values compared with the control mix (100% natural aggregate). Asi et al. [40] investigated the replacement of the natural limestone aggregate in asphalt mixtures with steel slag in terms of their resilient modulus, creep, wheel crack, and indirect tensile strength tests at five different percentages ranging between 0% to 100% in increments of 25%. The results showed an improvement in the tested mechanical properties for mixes up to 75%. In their study, Ziaee et al. [41] stated that the use of steel slag resulted in higher asphalt absorption, hence a higher optimum asphalt content of the asphalt mixtures. This conclusion agreed with the findings of Hassan at al. (2021) [42]. The increase in asphalt consumption can be attributed to the shape irregularity, high air content, and porous texture of the steel slag, as suggested by [34,40,43,44]. In addition, the physical properties of the steel slag, which are similar to sand, made them adhere well to the asphalt cement. The irregularity of the steel slag particles caused high internal frictional force inside them and their small shrinkage helped in preventing volume shrinkage resulting from the temperature changes [45].

Introducing steel slag to RAP mixtures has also been an investigation topic for some researchers [38,46,47]. The main conclusion has been the suitability of using steel slag as a replacement in the hot asphalt mixture/incorporated RAP aggregate. In particular, Fakhri and Ahmadi [26,29] observed that incorporating RAP with steel slag improved the dynamic creep, resilient modulus, fatigue life, and indirect tensile strength of asphalt mixes. They

also remarked that as the RAP content increased, the moisture susceptibility of the mixtures reduced. However, the opposite observation was found in Yang et al.'s [48] experimental research, where the addition of RAP increased the moisture susceptibility for both hot and warm asphalt mixes. The loose honeycomb porous structure, high texture, and angularity of the steel slag [24] improved the adhesion and mechanical properties of the recycled asphalt hot mixtures, as reported by Yang et al. [49]. The enhancement included mainly their rutting and cracking resistance, fatigue performance, and moisture susceptibility. They suggested using steel slag in mixes containing 70% RAP, as it demonstrated the looked-for performance plus met the asphalt pavement's upper surface design requirements.

Silica fume (SF) is also a byproduct material that has been limitedly studied within the asphalt paving industry in recent years. It comes from the smelting process in the elemental silicon and ferrosilicon alloy production in electric arc furnaces [50,51]. Additionally, their very fine particles have a mean size of 0.1–0.3 μm [52–54]. The addition of the silica fume to the asphalt mixtures showed its effectiveness in lowering the asphalt cement content [52], decreasing the stiffness modulus [55], and improving the fatigue life [56]. Al-Zajrawi et al. [57] studied the silica fume effect on hot asphalt mixtures concerning the Marshall stability and flow parameters. They found that, compared with the conventional mixes, the ones with silica fume apart from filler aggregate showed higher tensile strength resistance, stability, and flow values. The increase in stability ranged between 31% and 59%. A similar study by Al-Taher et al. [58], showed an increase in the Marshall stability and flow by about 23.61% and 4.67%, respectively. They also concluded the influence of adding silica fume to the asphalt mixes, in terms of reducing the rutting depth and increasing the indirect tensile strength of the tested asphalt mixtures. In 2021, Aboelmagd et al. [59] investigated the mechanical properties of asphalt mixes with nano-silica fume prepared at low and high contents. The properties included stiffness, rutting, fatigue life, and moisture damage of these mixes. The study results indicated an improvement in the rheological and physical properties of the hot asphalt mixtures prepared with high contents of nano-silica fume. The high contents were 30%, 40%, and 50%, respectively. Moreover, the modified mixtures showed more resistance to rutting, fatigue cracking, and moisture damage when compared with the control mix.

The works conducted so far using the byproduct materials have mainly focused on using them as a coarse aggregate alternative. To the best of our knowledge, limited studies have considered the use of these additives as a filler replacement in hot asphalt mixtures prepared with RAP at different ratios. Therefore, the aim of this study was to investigate the effect of adding steel slag and silica fume to the optimum asphalt binder content in addition to determining the asphalt content demand. The Marshall mix design method was preferred for its simplicity, affordability, portability, and ability to produce mixes with densities closer to real pavement densities (field densities). Both the Marshall stability and the flow testing properties were conducted to find the suitable mix that will prevent deformation from axle loads. The asphalt mixtures were prepared and tested following the American Society for Testing and Materials (ASTM) provisions.

2. Materials and Methods

For the aim of this study, the crushed limestone recycled aggregates were used for preparing the hot asphalt mixtures. Figure 1 summarizes the experimental work. The tested properties of these aggregates are provided in Table 1. Figure 2 shows their gradation with a nominal maximum size of 19 mm. The gradation of the coarse aggregate ranged between 19.5 mm and 4.75 mm, whereas the fine aggregate ranged from 2.36 mm to 0.075 mm.

Asphalt cement with a 60/70 penetration grade (ASTM D5-20 [60]), obtained from a local company, was used for all the asphalt mixtures in the investigation. Additional characteristics of the asphalt were tested and are shown in Table 2. Four percentages of RAP aggregates were studied, including 25%, 50%, 75%, and 100%, respectively. The resulting asphalt content of the RAP material, determined by quantitative extraction following the ASTM D2172 guidelines [61], was equal to 5.25% by weight of the aggregate.

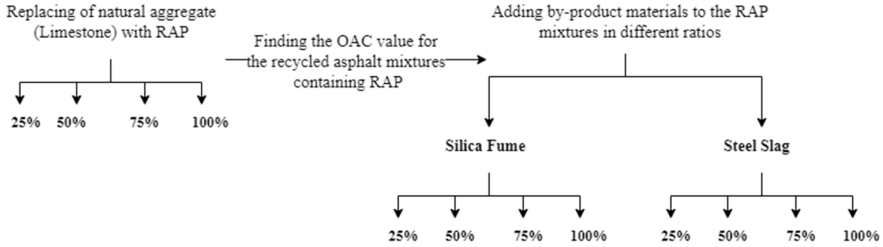

Figure 1. Experimental work flowchart.

Table 1. Typical properties of the aggregate material used for the control mix.

Test Type	Aggregate Material						Standard Methods (Specifications)
	Limestone			RAP			
	Coarse	Fine	Filler	Coarse	Fine	Filler	
Bulk specific gravity	2.45	2.35	1.61	2.39	2.34	1.91	ASTM C127 [62], ASTM C128 [63]
Absorption (%)	8.61	9.45	13.71	1.25	3.15	8.53	ASTM-C127 [62]
Los Angeles abrasion (%)		22.54			10.31		ASTM C131 [64]

Table 2. Technical properties of the virgin asphalt cement.

Test Type	Asphalt Cement Material	Standard Methods (Specifications)
	Asphalt Binder	
Specific gravity	1.01	ASTM-D70-21 [65]
Softening point (°C)	60	ASTM-D36-20 [66]
Ductility at 25 °C (cm)	+100	ASTM-D113-17 [67]

The preparation of these surface type asphalt mixtures was according to the Marshall design method, mainly to obtain the optimum asphalt content, based on the maximum stability for each RAP mix. Consequently, for these optimum asphalt mixes, the addition of the undensified silica fume and steel slag was applied in different ratios. These are the 25%, 50%, 75%, and 100% by the weight of the filler proportion from the total aggregate used. Figure 3 shows the steel slag gradation and after crushing.

The virgin asphalt cement was added and mixed simultaneously with the crushed limestone, RAP, and the investigated additives in a heated lab mixer for 5 min at medium speed and an extra 5 min at a higher speed rate. Both aggregates (i.e., limestone and RAP) were preheated for 24 h at (103–105) °C to be mixed with the other materials. Three mixes for each asphalt content were tested in their Marshall stability, therefore the total number of mixtures made was 234. The asphalt mixtures were compacted using the Marshall compaction apparatus (ASTM D6926-20 [68]) at 75 blows on each side, as specified for heavy traffic surface and base pavement design.

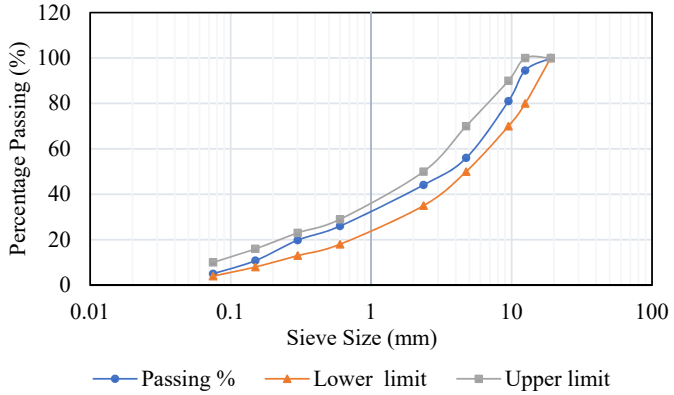

Figure 2. Design grading curves of the tested hot asphalt mixes, ASTM D3515-01 [69].

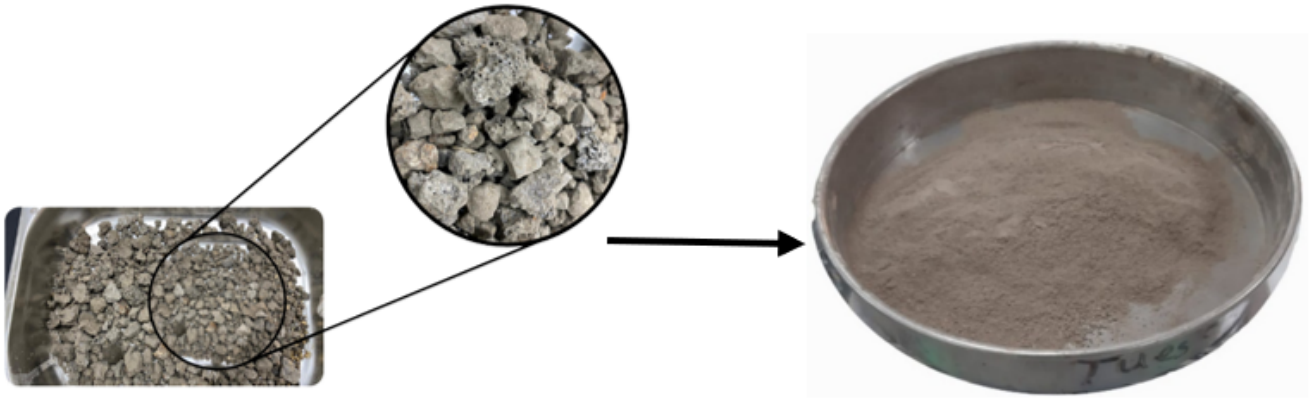

Figure 3. The steel slag material used before and after being crushed.

Marshall stability and flow tests were conducted in two phases. The first phase included mixes containing RAP materials that were prepared with various asphalt levels to determine their optimum asphalt content (OAC); therefore, in the second phase, new RAP mixes with the corresponding OAC at different percentages of additives were prepared and tested.

3. Results and Discussion

3.1. Reclaimed Asphalt Pavement

The test results of the first phase evidenced the effectiveness of using the RAP aggregates as a replacement for the natural aggregate with the hot asphalt mixtures. Table 3 presents the test results for the mixes containing limestone only. In general, mixtures with RAP exhibited higher stability values than those made with limestone (see Table 4). The maximum stability values for the 75% and 100% RAP mixes were recorded respectively at a 2% AC level, showing less demand in the asphalt content. On the other hand, the lower percentages of RAP needed additional asphalt cement to attain their maximum stability, as shown in Figure 4a.

Table 3. Test results for the mix prepared with limestone only.

Test Type	Asphalt Cement (%)					
	4	**4.5**	**5**	**5.5**	**6**	**6.5**
Stability (kN) [70]	10.37	12.24	13.88	16.05	15.29	7.58
Flow (mm) [70]	3.27	3.26	3.27	3.17	4.75	14.80
Air voids (%) [71]	6.71	5.14	4.71	3.58	1.47	0.99
VMA (%)	23.71	23.05	19.11	18.54	20.49	20.38
VFA (%)	71.72	77.71	75.36	80.70	92.80	95.13
Unit weight (kg/m^3) [72]	1750.92	1775.48	1876.15	1899.32	1863.73	1876.22

Except in the case of the 25% RAP mix, adding RAP material increased the flow values for three tested percentages as the asphalt content increased (see Figure 4b). This increase, however, exceeded the ASTM standards for heavy traffic pavements. Moreover, additional violations in the limits of the standards were observed in the air voids, VMA, and VFA, respectively, as can be seen in Figure 4c–e. This can be attributed to the reduction in the active asphalt content and to the differences in the asphalt content viscosity due to aging [4,73]. It can be concluded that increasing RAP quantities is proportionally affected by the stiffness, which means that adding RAP material results in a stiffer asphalt mixture. Therefore, in the second phase, using chemical and byproduct materials as a filler was

investigated at 25%, 50%, 75%, and 100%, respectively. Figure 4f shows the asphalt content versus the unit weight values for all tested mixes.

Table 4. Test results for the tested mix prepared with RAP aggregate.

Test Type	Test Mix	Asphalt Cement (%)									
		1	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**
Stability (kN) [70]	25% RAP	-	-	-	-	10.06	14.88	17.82	13.72	10.59	-
	50% RAP	-	-	-	14.24	16.44	14.01	11.26	9.00	6.81	-
	75% RAP	8.54	15.36	19.38	17.24	16.06	14.57	12.08	9.15	6.56	5.19
	100% RAP	14.47	18.21	23.22	20.52	17.74	14.00	10.23	8.09	5.35	4.99
Flow (mm) [70]	25% RAP	-	-	-	-	7.54	6.12	5.48	4.87	4.21	-
	50% RAP	-	-	-	4.69	5.12	5.90	7.26	8.16	10.60	-
	75% RAP	4.29	4.90	5.16	6.63	7.26	8.47	9.26	14.54	18.22	19.75
	100% RAP	3.64	4.03	4.56	4.99	5.58	6.65	11.05	12.34	16.28	19.93
Air voids (%) [71]	25% RAP	-	-	-	-	3.53	3.76	4.21	4.55	5.27	-
	50% RAP	-	-	-	1.97	2.26	2.57	3.11	3.91	4.29	-
	75% RAP	3.55	3.36	3.16	2.99	2.86	2.64	2.48	1.46	1.40	1.20
	100% RAP	3.88	3.35	2.14	1.89	1.65	1.40	1.30	1.08	0.97	0.90
VMA (%)	25% RAP	-	-	-	-	10.73	10.99	11.51	12.17	12.76	-
	50% RAP	-	-	-	10.67	10.78	11.45	12.10	12.74	13.46	-
	75% RAP	6.86	7.15	7.43	8.06	8.73	9.43	10.06	10.75	11.32	12.06
	100% RAP	6.69	6.97	7.58	8.13	8.70	9.40	10.06	10.71	11.57	12.55
VFA (%)	25% RAP	-	-	-	-	67.08	65.78	63.45	62.64	58.72	-
	50% RAP	-	-	-	81.51	79.01	77.56	74.32	69.34	68.11	-
	75% RAP	48.27	53.04	57.47	62.91	67.20	72.03	75.39	86.38	87.67	90.04
	100% RAP	42.04	52.02	71.78	76.82	80.99	85.10	86.00	86.76	91.65	91.49
Unit weight (kg/m^3) [72]	25% RAP	-	-	-	-	2027.89	2032.32	2031.10	2026.40	2023.42	-
	50% RAP	-	-	-	2018.80	2026.78	2021.98	2017.43	2013.35	2007.23	-
	75% RAP	2073.01	2077.15	2081.36	2077.75	2073.26	2067.95	2064.23	2059.13	2056.79	2050.36
	100% RAP	2076.84	2081.00	2077.88	2076.14	2073.91	2068.62	2064.29	2060.08	2050.97	2039.04

The hot asphalt mixtures were prepared with various proportions of RAP at their optimum asphalt content (OAC). So, for asphalt mixes with higher RAP contents, the OAC was 2%, whereas, for the 25% and 50% RAP contents, the OAC was 4% and 3%, respectively. This observation of the asphalt content reduction agreed with the findings of some previous studies [6,14].

3.2. RAP Mixtures Prepared with Steel Slag

Incorporating steel slag into the RAP mixes, as shown in Table 5, improved the asphalt mixtures' mechanical and volumetric properties, attributing to the bulk-specific gravity of the steel slag [35,74]. The Marshall stability (see Figure 5a) showed a significant improvement for mixes containing 50% and 75% RAP contents when adding 75% and 50% of the fine steel slag material to the asphalt mixtures, respectively. The highest stability load recorded was 32.73 kN for mixes prepared with 75% RAP and 50% steel slag at 2% AC content. This observation agreed well with the findings of Rahat et al. [75]. The flow and air voids increased simultaneously as the steel slag levels increased, as shown in Figure 5b,c, respectively. The volumetric properties of the mix, including the VMA and

VFA, showed that, for the HMA containing lower RAP contents, the increase in the steel slag addition resulted in lower VMA values. However, it was the opposite trend in the 75% and 100% RAP mixes (see Figure 5d). The voids filled with asphalt showed an increase in their results, as seen in Figure 5e, upon using higher RAP and steel slag contents, caused by the asphalt binder extenders due to the increase in the fine particles [75]. Lastly, the unit weight values showed the contrast relation between the tested mixes, for which the 25% and 50% RAP mixtures had an ascending trend with the increase in the steel slag replacement levels, whereas, for the 75% and 100% RAP mixes, the descended trend was observed (see Figure 5f).

Table 5. Test results for the RAP mixes containing steel slag.

Test Type	Test Mix	Steel Slag (SS) Replacement			
		25%	**50%**	**75%**	**100%**
Stability (kN) [70]	25% RAP	4.85	8.83	11.73	8.39
	50% RAP	13.38	15.5	22.84	15.82
	75% RAP	21.91	32.73	26.17	25.53
	100% RAP	18.43	19.57	16.9	14.74
Flow (mm) [70]	25% RAP	5.67	6.79	7.87	9.13
	50% RAP	5.56	5.91	6.79	8.78
	75% RAP	3.29	3.51	4.35	4.71
	100% RAP	4.41	4.66	4.89	5.27
Air voids (%) [71]	25% RAP	4.31	4.50	4.76	4.97
	50% RAP	2.93	3.26	3.37	3.45
	75% RAP	4.14	4.12	4.44	4.68
	100% RAP	3.86	3.93	4.12	4.69
VMA (%)	25% RAP	10.86	10.54	10.16	9.73
	50% RAP	10.96	10.63	10.32	9.72
	75% RAP	12.12	12.33	12.62	13.56
	100% RAP	12.67	12.74	12.76	12.85
VFA (%)	25% RAP	60.33	57.31	53.16	48.94
	50% RAP	73.23	69.33	67.38	64.48
	75% RAP	65.87	66.55	64.82	65.48
	100% RAP	69.54	69.12	67.72	63.47
Unit weight (kg/m^3) [72]	25% RAP	2045.95	2053.34	2061.97	2071.83
	50% RAP	2022.69	2030.11	2037.06	2050.87
	75% RAP	1975.89	1971.18	1964.74	1943.50
	100% RAP	1963.50	1962.00	1961.44	1959.47

RAP Mixtures Prepared with Steel Slag Tested under Water

Table 6 shows the test results of the tested asphalt mixtures prepared with different steel slag replacement ratios under the presence of water. As shown in Figure 6, the addition of steel slag resulted in reducing the strength capacity of these mixtures after curing. The stability values for the 25% RAP mixes decreased from 11.73 kN to 9.84 kN (i.e., a 16.11% decrease), as shown in Figure 6a, whereas for the 50% RAP mixes the reduction was in the neighborhood of 11.55% (see Figure 6b). In contrast, the presence of water for the asphalt mixes containing large RAP quantities with different steel slag ratios showed nearly similar performance in terms of its Marshall stability. The 75% RAP mix showed only a 0.55%

reduction in their strength (see Figure 6c), while it was 6.49% for the mixtures prepared with the 100% RAP aggregate (see Figure 6d). The decrease in the stability and strength of the asphalt mixtures may have been caused by the increase in the water erosion time leading to the increase in the pH value, reducing the steel slag adhesion and accelerating the hydration process on the steel slag surface [76,77]. The findings of using the steel slag as a filler material in underwater environments indicated its effectiveness in achieving less variation in the stability values after curing for 4 days at 50 °C, following the ASTM D1075-07 [77] procedures.

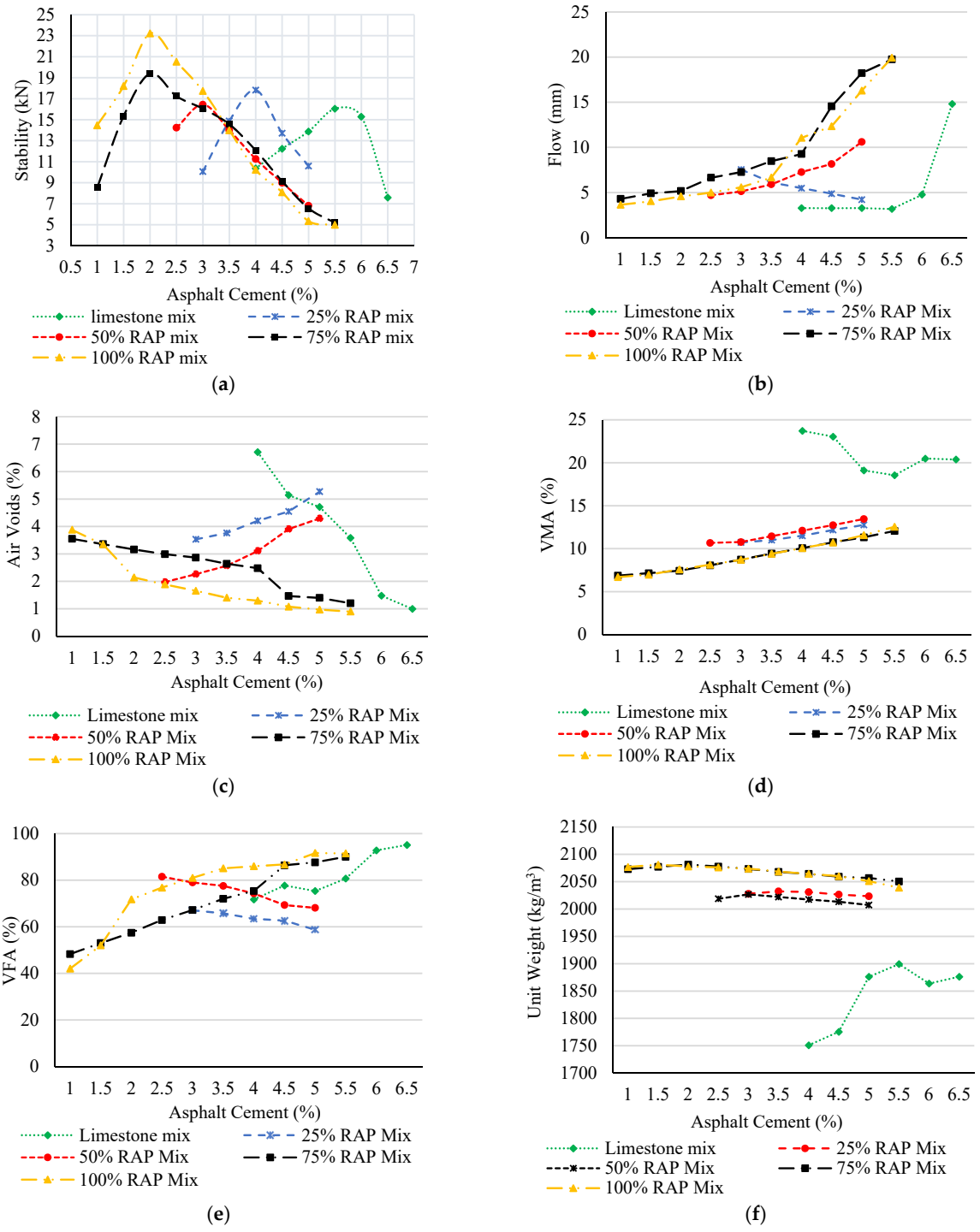

Figure 4. Test results of the asphalt mixes containing RAP in terms of (**a**) Marshall stability; (**b**) flow; (**c**) unit weight; (**d**) air voids; (**e**) VMA; (**f**) VFA.

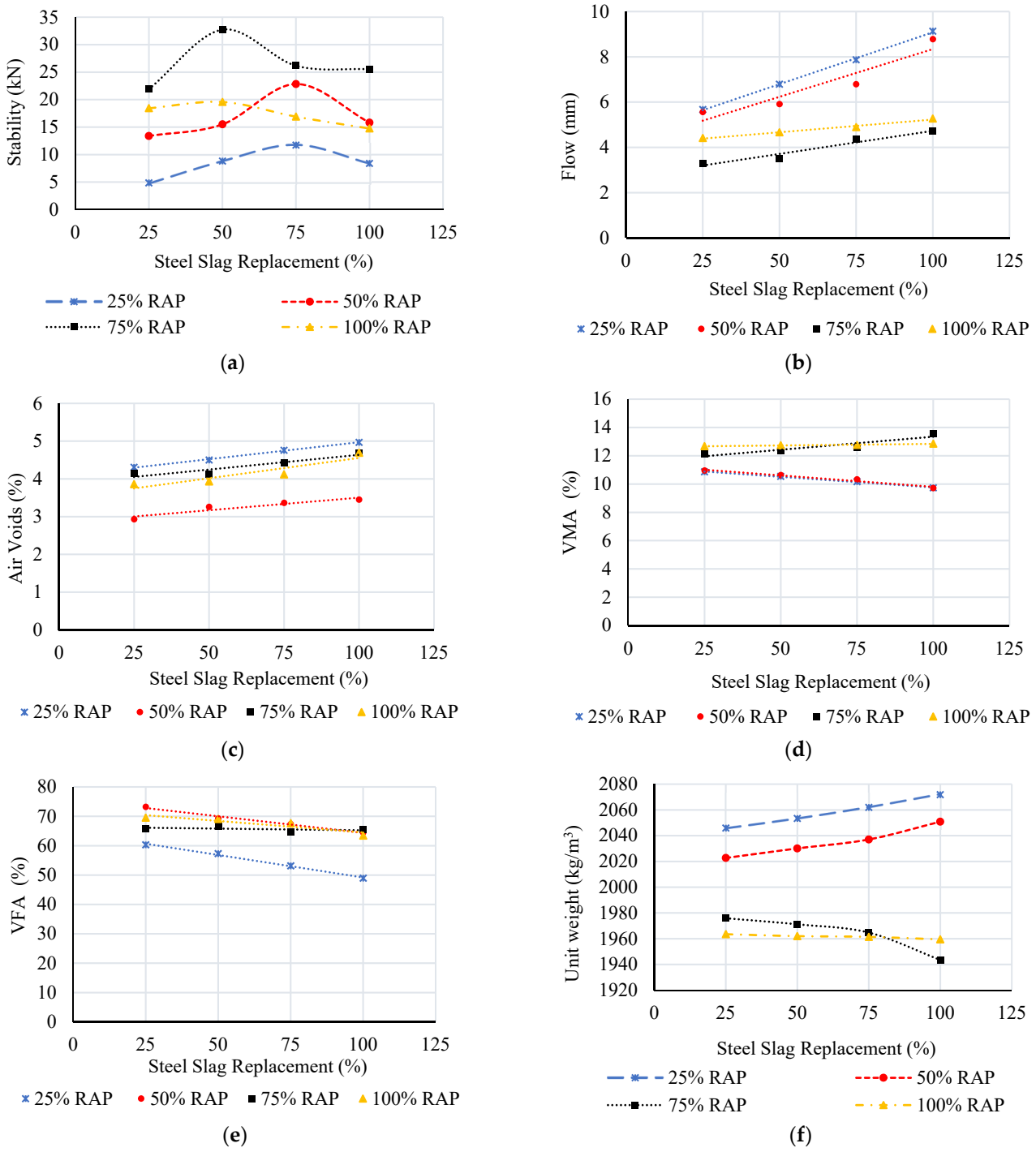

Figure 5. Test results of the RAP mix prepared with steel slag material in terms of (**a**) Marshall stability; (**b**) flow; (**c**) unit weight; (**d**) air voids; (**e**) VMA; (**f**) VFA.

3.3. RAP Mixtures Prepared with Silica Fume

Table 7 provides a summary of the Marshall test results for all the RCA mixtures. Adding un-densified silica fume to the asphalt mixes containing RAP showed an improvement in the stability results, as depicted in Figure 7a. The 25% RAP mix failed when curing before testing, whereas the remaining mixes achieved the minimum Marshall stability limit of 8 kN but failed to satisfy the flow requirements, mainly for the 50% RAP mix (see Figure 7b). With its high air voids, the 75% RAP mix prepared with silica fume varied from the two other tested RAP mixes, as shown in Figure 7c. The same observation was found in the VMA parameter (see Figure 7d). This variation in the volumetric properties

may be attributed to the alkali chemical reaction resulting from the high surface area and amorphous silica contents in the silica fume [78]. No significant differences were noticed in Figure 7e related to the voids filled with asphalt values. The unit weight results (see Figure 7e) depicted variances between the RAP mixes containing SF. The fine nature of the silica fume particles blocked the voids and therefore increased the density of the asphalt mixture, as reported in the Alia Al-Ani study [79].

Table 6. Test results for the tested mixes with steel slag under water for 4 days at 50 °C.

Test Mix		Before Curing		After Curing	
		Stability (kN)	Flow (mm)	Stability (kN)	Flow (mm)
25% RAP at 4% AC	25% SS	4.85	5.67	4.02	5.24
	50% SS	8.83	6.79	6.54	6.59
	75% SS	11.73	7.87	9.84	6.97
	100% SS	8.39	9.13	4.78	8.53
50% RAP at 3% AC	25% SS	13.38	5.56	12.69	5.65
	50% SS	15.50	5.91	14.59	6.02
	75% SS	22.84	6.79	20.20	6.54
	100% SS	15.82	8.78	13.47	8.70
75% RAP at 2% AC	25% SS	21.91	3.29	21.15	3.68
	50% SS	32.73	3.51	32.55	3.42
	75% SS	26.17	4.35	22.52	4.31
	100% SS	25.53	4.71	20.33	4.64
100% RAP at 2% AC	25% SS	18.43	4.41	17.25	4.23
	50% SS	19.57	4.66	18.30	4.54
	75% SS	16.90	4.89	14.95	4.78
	100% SS	14.74	5.27	11.87	5.20

Table 7. Test results for the RAP mixes containing silica fume.

Test Type	TEST Mix	Silica Fume (SF) Replacement			
		25%	50%	75%	100%
Stability (kN) [70]	50% RAP	8.9	10.49	11.95	13.94
	75% RAP	23.16	26.19	28.74	31.02
	100% RAP	15.21	21.35	23.62	25.86
Flow (mm) [70]	50% RAP	5.13	5.24	5.55	6.75
	75% RAP	4.12	3.81	3.75	3.5
	100% RAP	4.38	4.27	4.06	3.92
Air voids (%) [71]	50% RAP	3.79	3.98	4.13	4.35
	75% RAP	4.28	4.54	4.70	4.86
	100% RAP	3.78	3.95	4.13	4.24
VMA (%)	50% RAP	10.69	10.74	10.83	10.90
	75% RAP	12.62	12.86	13.65	14.01
	100% RAP	11.42	11.50	11.82	12.14
VFA (%)	50% RAP	64.56	62.93	61.82	60.09
	75% RAP	66.09	64.68	65.57	65.29
	100% RAP	66.91	65.69	65.06	63.77
Unit weight (kg/m^3) [72]	50% RAP	2028.85	2027.72	2025.67	2024.00
	75% RAP	1964.74	1959.37	1941.53	1933.39
	100% RAP	1991.57	1989.79	1982.68	1975.46

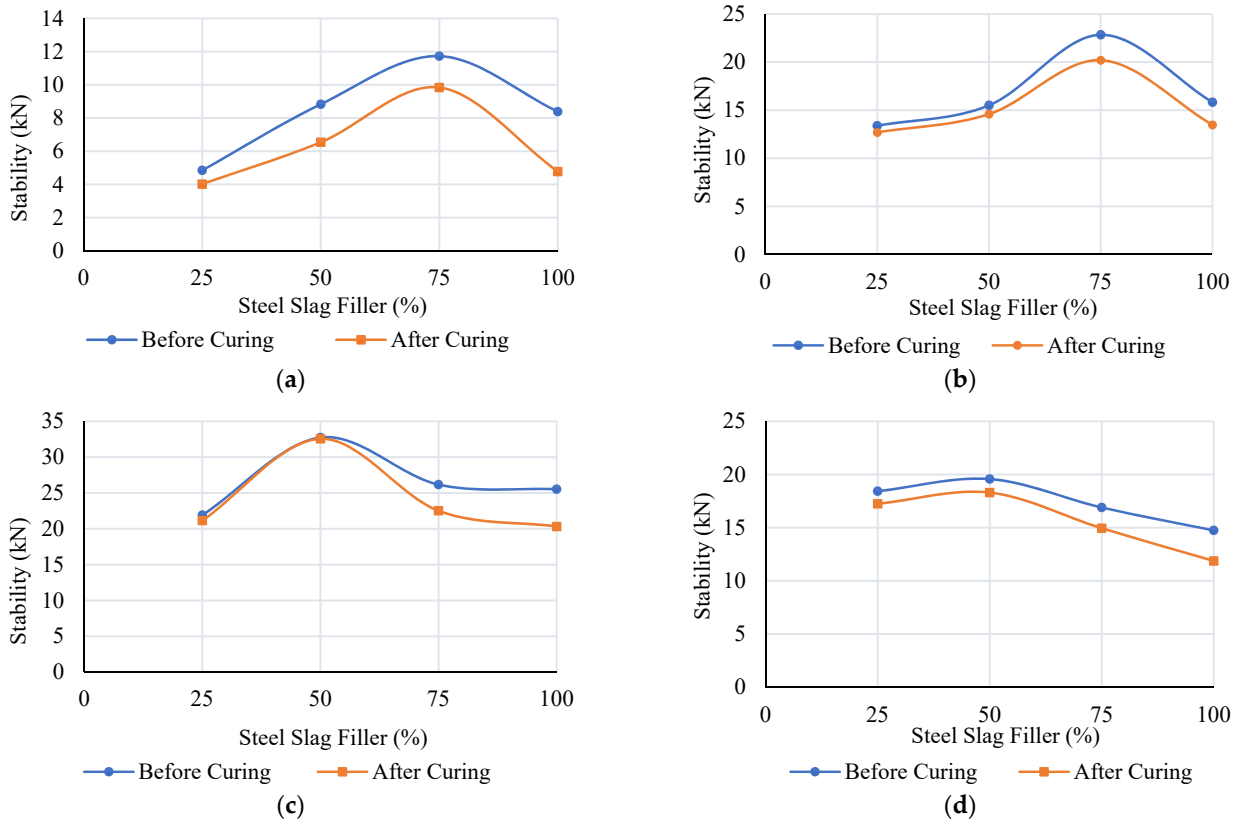

Figure 6. Marshall stability values for the asphalt mixes tested under water and prepared with (**a**) 25% RAP; (**b**) 50% RAP; (**c**) 75% RAP; (**d**) 100% RAP.

Considering the financial aspects, using silica fume showed its feasibility, as it was locally produced and thus economically viable, with a maximum price value of 1 kg at USD 40. Moreover, the recycling of the raw and waste materials had a positive impact on the environmental and economic perspectives since they did not have any value for money, specifically for this study.

Compared with the RAP mixes/incorporated steel slag, the asphalt mix prepared with 100% RAP + 100% SF should have the highest enhancement relative to the 100% RAP control mix, whereas a similar performance was observed for the 75% RAP + 75% SF.

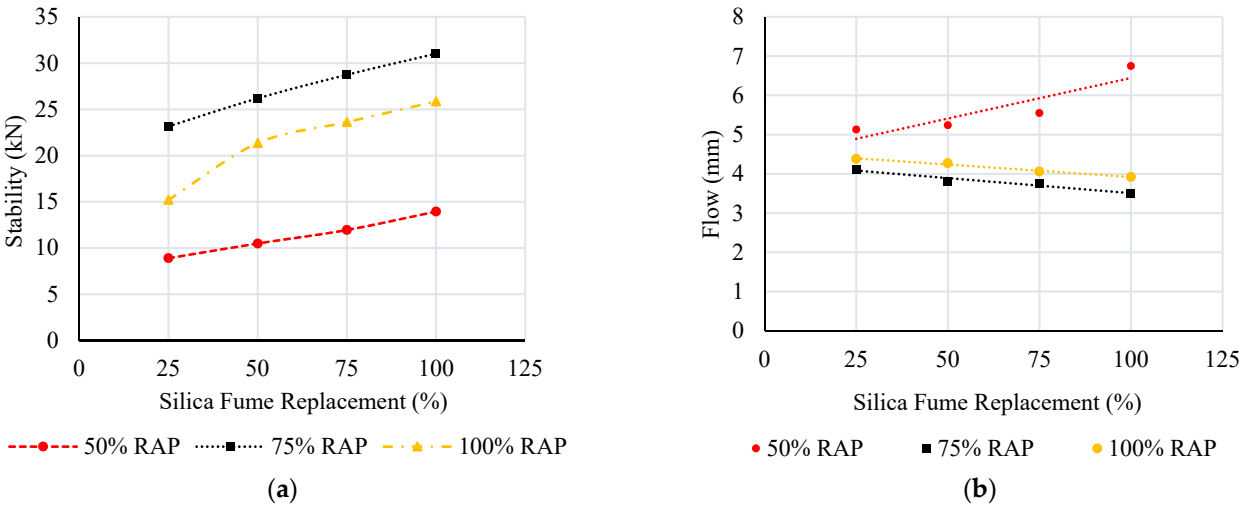

Figure 7. *Cont.*

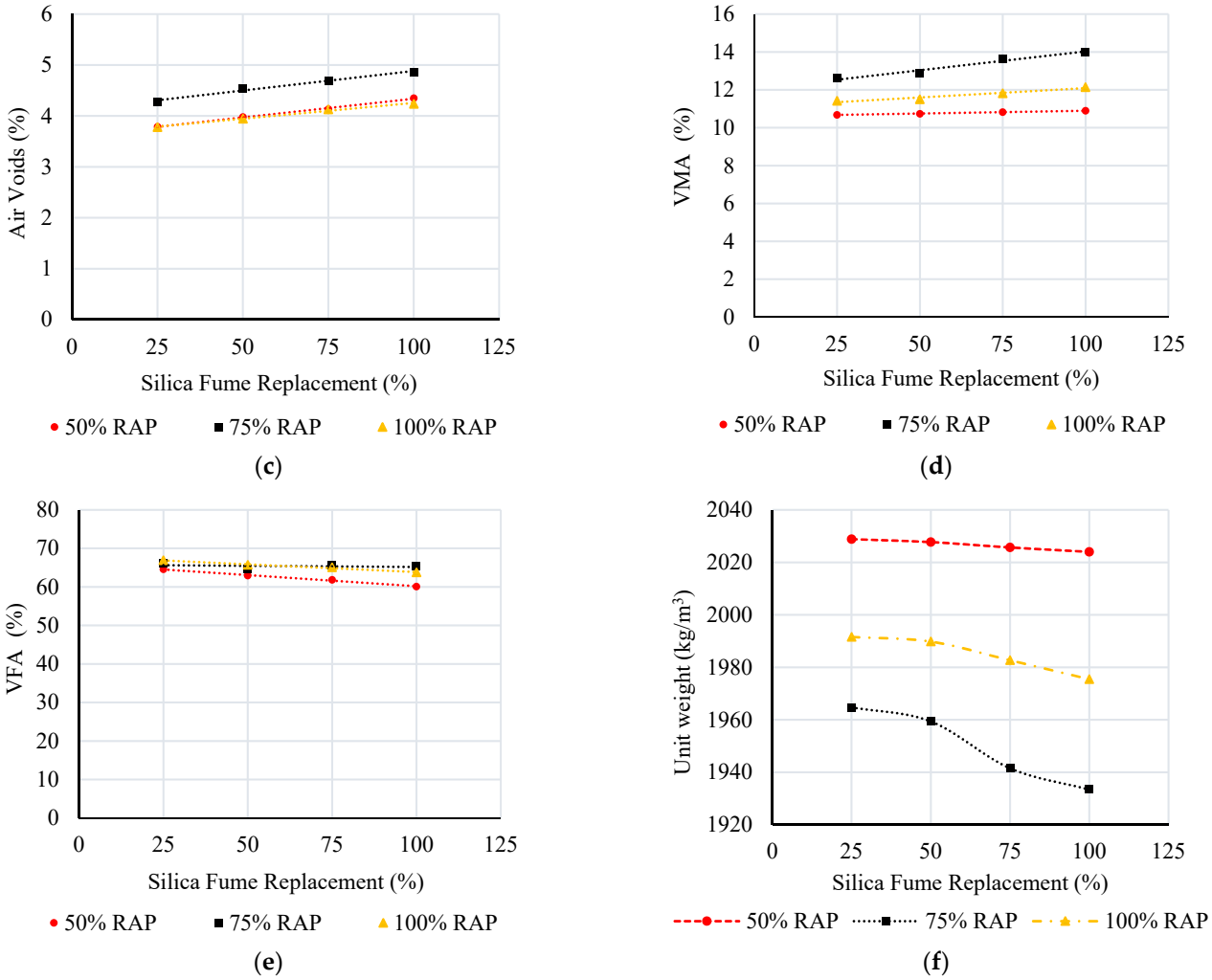

Figure 7. Test results of the three recycled aggregate mixes prepared with silica fume in terms of (**a**) Marshall stability; (**b**) flow; (**c**) unit weight; (**d**) air voids; (**e**) VMA; (**f**) VFA.

4. Conclusions

The experimental study discussed in this paper evaluates the use of steel slag and silica fume materials on the mechanical properties of the hot asphalt mixtures containing RAP aggregate at different percentages. Based on the results, the following conclusions were drawn:

I. Adding RAP aggregate in large quantities increased the stability and decreased the optimum asphalt content, especially in the case of the 100% RAP mix, which recorded 23.22 kN at 2% asphalt content.
II. The use of steel slag at 50% and 75% proved its effectiveness in improving the mechanical and volumetric properties of the recycled mixtures with a percent improvement of 38.92% and 68.88%, respectively.
III. The highest stability reached for mixes prepared with different proportions of 75% and 50%, respectively, of the RAP and steel slag materials.
IV. Introducing water to the recycled asphalt mixtures containing steel slag showed a decrease in the Marshall stability values yet maintained the ASTM requirements. Nonetheless, the 75% RAP mix sustained its high stability load of 32.55 kN after curing at 50 °C.
V. Significant behavior related to the stability was observed for asphalt mixtures with silica fume. The 75% RAP mix prepared with different silica fume ratios showed

stability improvement, with the highest value of 31.02 kN recorded at a 75% silica fume addition.

To further evaluate the performance of the recycled asphalt mixtures, the authors recommend detailed experimental research that includes the indirect tensile strength test, permanent deformation, thermal cracking, fatigue, and moisture damage considering the optimum asphalt mixes obtained in this research for the steel slag and silica fume additives, respectively.

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