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The Influence of a Field-Aged Asphalt Binder and Aggregates on the Skid Resistance of Recycled Hot Mix Asphalt

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Abstract: The application of asphalt hot mix recycling is one challenge in sustainable road pavement research. In addition to the vast amount of research on the performance of recycled asphalt–concrete, the research on the frictional resistance of recycled hot mix asphalt is still limited. The effects of aged asphalt and aged aggregates on the skid resistance of recycled hot mix asphalt were investigated in this research. The aged asphalt and aged aggregates were carefully extracted from the field-reclaimed asphalt pavement, and the engineering and mechanical properties of aged and virgin aggregates were measured. The degradation of recycled hot mix asphalt was simulated using an accelerated polishing machine to mimic road surface abrasion. Accordingly, the initial and final skid resistances of the recycled hot mix asphalt were determined and correlated with the properties of the aged asphalt and aggregates. The initial skid resistance of recycled hot mix asphalt decreased with reductions in penetration and ductility of the blended asphalt. However, the changes in the blended asphalt properties contributed only small variations to the final skid resistances of the recycled hot mix asphalt. The gradations of recycled hot mix asphalt correlated only with the final skid resistances. The aggregate gradations controlled the characteristics of the final skid resistance since the covered binder was partially polished off from the road surface at this stage.

Keywords: asphalt hot mix recycling; reclaimed asphalt pavement; aged asphalt; aged aggregates; skid resistance

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1. Introduction

The construction of new road pavement generally consumes concerning amounts of natural resources. It also produces solid waste and emits greenhouse gases [1]. Therefore, road pavement construction with an extended service lifetime is the ideal strategy for sustainable roads [2]. Aside from achieving a longer service lifetime for road pavement structures [3,4], employing recycled materials in road construction is another widespread approach to reducing the environmental impact of road construction [5]. Therefore, recycled asphalt pavement, or reclaimed asphalt pavement (RAP), is increasingly employed as the main source for hot mix asphalt [6]. The benefit of using RAP as the recycled aggregate is the reduced consumption of virgin asphalt and virgin aggregates in new road construction. In the USA, reusing RAP reduced the usage of virgin asphalt and virgin aggregates by 4.1 and 78 million tons in 2018, respectively [6]. In Thailand, the applications of recycled asphalt–concrete or recycled hot mix asphalt are limited to patching road surfaces and remedial works [7].

Previous Research Works

Previous studies have reported that uncertain test results are usually observed from the mixtures with high RAP contents. This variation in mixture performance is mainly caused by inappropriate mixture design [8]. For the asphalt recycling mixture design, an amount of RAP equivalent to ≤25% by mass can be incorporated into the mixture without binder modification. However, a blending chart is recommended by AASHTO M 323 [7] if the amount of RAP in the mixture is greater than 25% [7,8]. Modification of the binder, which uses a higher grade of asphalt binder, is required to compensate for the stiff responses of the highly aged asphalt present in the RAP. However, past research on recycled asphalt–concrete mostly examined the performance, workability, and constructability of the recycled pavement mixtures [9–11].

Previous research illustrates that an increased amount of RAP in the recycled hot mix asphalt may slightly improve the rutting resistance of the mixture. However, the fatigue resistance of recycled hot mix asphalt is generally reduced by the aged asphalt [10]. Therefore, additives, recycling agents, or rejuvenators are required during asphalt hot mix recycling to improve the durability of the mixture and fatigue life [10,12]. The complex behaviour of recycled asphalt–concrete with a high RAP percentage is caused by the incomplete or partial blending between the aged asphalt and the virgin asphalt [13]. The mixing temperature, mixing time, amount of RAP, and size of virgin and aged aggregates are the factors that influence the degree of blending between the aged and virgin asphalt binders. To better understand the characteristics of recycled hot mix asphalt, knowledge of the rheological and engineering properties of aged and virgin asphalt binders is required [14].

The frictional, or skid, resistance of the road surface is an important parameter that controls the number of fatal road accidents [15]. The safety of pedestrians, drivers, and public transport users depends on the frictional characteristics of the road surface. Slippery road surfaces may cause fatal road accidents. Skid resistance depends on various factors, such as material properties (properties of aggregate, asphalt, and tire), construction methods, climate, and traffic [16]. There is a large body of research focused on various aspects of the skid resistance of road surfaces [17–24]. The National Center for Asphalt Technology (NCAT) is one of the leading research groups in skid resistance characteristics of the road surface [25–32]. The results from NCAT research have been used to establish the recent safety guidelines for road pavement construction in many countries.

In summary, the previous research on asphalt hot mix recycling mostly focused on performance improvement and incorporating more RAP into the mixtures. Research on the frictional characteristics of recycled hot mix asphalt is still limited. Moreover, the effects of recycled asphalt degradation due to vehicle abrasion on the skid resistance should be characterized; accordingly, the concept of safe and sustainable road pavement constructed with recycled materials can be fulfilled. To bridge this research gap, the effects of aged asphalt and aged aggregates on the skid resistance of recycled hot mix asphalt were characterized. The deterioration of recycled hot mix asphalt due to the traffic was simulated by an accelerated polishing machine. Therefore, the skid resistance of recycled hot mix asphalt at the initial and final stages (before and after operation) can be investigated.

2. Materials and Methods

2.1. Materials

2.1.1. Virgin Aggregates

Limestone produced from the quarry in Sukhothai Province, Thailand, was used as fresh, or virgin, aggregates. The quarry produced four stockpiles of different sizes of aggregates. These aggregate stockpiles were sorted according to their nominal maximum size of aggregates (NMSA), which are dust, 9.5, 12.5, and 19.0 mm. bins. According to specification No. DH-S 408 [33], the properties of aggregates met the Department of Highways (DOH) requirements. The gradation of virgin aggregates is shown in Table 1. The aggregate physical and index properties are presented in Table 2.

Table 1. The gradations of virgin aggregates and reclaimed asphalt pavement (RAP).

Sieve Size (mm)	25.0	19.0	12.5	9.5	4.75	2.36	1.18	0.60	0.30	0.15	0.075
				Virgin aggregates (Limestone)							
Dust	100	100	100	100	99.7	73.1	47.4	32.1	24.6	19.0	15.6
9.5 mm	100	100	100	94.8	2.9	0.3	0	0	0	0	0
12.5 mm	100	100	94.4	21.9	0.02	0	0	0	0	0	0
19.0 mm	100	86.4	6.28	0	0	0	0	0	0	0	0
				Reclaimed asphalt pavement (RAP)							
Coarse RAP (CR) 5–20 mm	98.4	92.2	77.2	58.6	4.29	0	0	0	0	0	0
Fine RAP (FR)	100	100	100	100	97.0	52.5	24.3	5.7	2.1	1.1	0.7

Table 2. Physical and index properties of virgin aggregates (limestone).

Property	Virgin Aggregate					Standard Requirements
	Fine		Coarse			
	Passing #200	Retained #200	9.5 mm	12.5 mm	19.0 mm	
Bulk specific gravity	-	2.651	2.714	2.710	2.714	-
Apparent specific gravity	2.727	2.686	2.699	2.674	2.679	-
Water absorption (%)	-	1.42	0.60	0.50	0.48	-
Flakiness index (%)	-			26.0		≤35
Elongation index (%)	-			31.1		≤35
Soundness (%wt. Loss)	coarse aggregate = 1.73, fine aggregate = 2.38					<9
Sand equivalent (%)	84.4					≥50

2.1.2. Reclaimed Asphalt Pavement (RAP)

The RAP used in this research was selected from one of the stockpiles located in Phitsanulok Province, Thailand. Information received from the office of Highway No. 5 Phitsanulok (DOH) indicated that the RAP was milled from the pavement surface, which had a service lifetime of approximately 5 years. The extraction experiment employed in this research reported that the amount of aged asphalt content was equivalent to 4.7%. The gradation of the selected RAP is shown in Table 1. The RAP was pre-processed to divide the aggregates into two different sizes. The fine RAP (FR) has a particle size smaller than 4.75 mm (passing sieve no. 4). The aggregates extracted from RAP are referred to as the "aged aggregates". Table 3 illustrates the physical and index properties of aged aggregates obtained from laboratory tests. Table 3 demonstrates that the aggregates extracted from RAP were suitable as new asphalt aggregates based on standard no. DH-S 410 [34]

Table 3. Physical and index properties of aged aggregates (aggregates extracted from RAP).

Property	Aged Aggregate					Standard Requirements
	Fine		Coarse			
	Passing #200	Retained #200	9.5 mm	12.5 mm	19.0 mm	
Bulk specific gravity	-	2.653	2.758	2.798	2.799	-
Apparent specific gravity	2.704	2.719	2.771	2.821	2.819	-
Water Absorption (%)	-	0.91	0.17	0.29	0.25	-
Flakiness Index (%)	-			32.4		≤35
Elongation Index (%)	-			9.5		≤35
Soundness (%wt. Loss)	coarse aggregate = 0.10, fine aggregate = 1.91					<9
Sand Equivalent (%)	90.0					≥50

2.1.3. Virgin Asphalt

This research used type AC 60/70 virgin asphalt to produce the hot mix asphalt and recycled hot mix asphalt based on DOH specification No. DH.-SP 401 [35]. AC 60/70 is the asphalt binder defined by penetration values between 60–70 dmm. (penetration grade).

2.2. Test Methods

2.2.1. Tests of Engineering Properties of Aggregates

The properties of aged aggregates and virgin aggregates determined in this research were the aggregate impact values (AIV) [36], aggregate crushing values (ACV) [37], Los Angeles abrasion (LAA) [38], and polished stone value (PSV) [39]. In this research, these properties were analyzed for the skid resistance of the asphalt–concrete mixtures since they represent the strength (AIV and ACV) and abrasion resistance (LAA and PSV) of the source aggregates.

2.2.2. Extraction of Aged Asphalt Binder and Aged Aggregates from the RAP

Aged asphalt and aged aggregates were extracted from RAP as presented in Figure 1. First, 2 kg of RAP was soaked in a dichloromethane solution (CH_2Cl_2) overnight. Then, the mixture was spun in the extraction unit bowl (Test Method A according to ASTM D2172 [40]). To separate the dissolved asphalt from the aged aggregates (Figure 1a). After the extraction step, the dissolved asphalt (aged asphalt and dichloromethane) was centrifuged (Figure 1b) to precipitate the fine aggregate particles from the solution. Finally, to extract the aged asphalt from the solution, a rotary evaporator was used according to ASTM D 5404 [41] as shown in Figure 1c. The aged aggregates were stored in a cool and dry place (room temperature) before further laboratory tests were conducted.

Figure 1. The extraction of aged asphalt binder and aged aggregates from RAP by (**a**) the extraction unit bowl, (**b**) the centrifuge, and (**c**) the rotary evaporator.

2.2.3. Chemical Characterization of Aggregates

X-ray diffraction (XRD) was performed to analyze the chemical composition of the virgin and aged aggregates using the Bruker D2 PHASER X-ray diffractometer. The sample aggregates were ground into a powder (passing sieve #200) before testing. The XRD of aged and virgin aggregates were then collected over a 2θ of 10–80°.

2.2.4. Design of the Asphalt–Concrete Mixture

The mixtures of asphalt and concrete were designed based on the Marshall method, according to the ASTM D1559 standard [42]. The optimum asphalt content and proper aggregate proportion of conventional hot mix asphalt were determined to comply with DH-S 408 standards [33]. This mixture is denoted as "V100" in Table 4. The same percentages of asphalt binder and proportion of aggregate were then applied to all the recycled hot mix asphalt mixtures. Table 4 shows that the optimum asphalt content of V100 was 5%; therefore, a total amount of binder equivalent to 5% was employed in the other three mixtures of recycled hot mix asphalt. The amount of aged asphalt was first calculated based on the amount of RAP in the mixture; then, sufficient virgin asphalt binder was added to keep the total amount of binder equivalent to 5%. As a result, the effects of the binder content can be neglected from the analysis.

Table 4. Summary results mix design of hot mix asphalt–concrete (V100).

Mix Design	V100 (CV50:FV50)
Proportion (%)	50:20:15:15 (Dust:9.5 mm:12.5 mm:19 mm)
Optimum asphalt content (%)	5.00
Density (gm/mL)	2.400
Air void (%)	3.3
Voids in mineral aggregate (VMA) (%)	14.0
Voids filled with bitumen (VFB) (%)	76.4
Stability (kN)	12.01
Flow (0.01″)	15.2
Remarks	V = Virgin aggregate, CV = Coarse virgin aggregate, FV = Fine virgin aggregate.

Moreover, to investigate the influences of FR and CR aggregates on the skid resistance of recycled hot mix asphalt, the ratio between fine and coarse aggregates was set to 50:50 for all mixtures. In this research, the fine aggregates are defined as the aggregates with particle sizes smaller than 4.75 mm. Therefore, based on Table 5, CR50:FV50 represents the mixture that contains 50% CR aggregates and 50% fine virgin (FV) aggregates. The mixture containing 50% coarse virgin (CV) aggregates and 50% FR aggregates is denoted by CV50:FR50. The R100, or CR50:FR50, is a mixture with 100% RAP aggregates, but the ratio between coarse and fine aggregates was maintained at 50:50. Accordingly, the aggregate proportion of all mixtures was kept the same to retain the 50:50 ratio between fine and coarse aggregates. In this research, an equivalent amount of aged asphalt contained in CR and FR aggregates were assumed. It is well known that a higher content of aged asphalt is usually encountered from the FR [8,13]; however, extracting the aged binder from separate FR or CR is not a common procedure for recycled hot mix asphalt concrete design. Therefore, the CR50:FV50 and CV50:FR50 mixtures were assumed to have the same aged asphalt content of 2.35% as shown in Table 5. Further investigation on the effects of precise amount of aged asphalt in FR and CR to the skid resistance should be performed in the future research.

Table 5. Summary proportion design of asphalt–concrete mix.

Mix Design		V100 (CV50:FV50)	CR50:FV50	CV50:FR50	R100 (CR50:FR50)
Proportion (%)	Dust	50	50	50	50
	9.5 mm	20	20	20	20
	12.5 mm	15	15	15	15
	19.0 mm	15	15	15	15
Total Asphalt (%) (Virgin: Aged Asphalt)		5.00 (5.0:0.0)	5.00 (2.7:2.35)	5.00 (2.7:2.35)	5.00 (0.3:4.7)
Remarks		V = Virgin aggregate, CV = Coarse virgin aggregate, FV = Fine virgin aggregate, CR = Coarse RAP aggregate, and FR = Fine RAP aggregate.			

2.2.5. Specimen Preparation for Abrasion Simulation

Hot mix asphalt and recycled hot mix asphalt slabs were manufactured for abrasion simulations. The three-wheel polishing device (TWPD) was used to simulate and accelerate the deterioration of the asphalt surface due to the vehicle tires. Therefore, the asphalt slabs were prepared with similar surface conditions to the field asphalt–concrete. The preparation steps are presented in Figure 2. First, the aggregates, RAP, and asphalt binder were batched according to the information provided in Table 5. The total weight of the asphalt–concrete mixture was approximately 30 kg per slab. Second, the mixture aggregates and RAP were loaded into the separate containers; after that, both containers were placed in the oven at a temperature of 170 °C for 4 h. The asphalt binder was also heated at 170 °C before it was mixed with the aggregates and RAP. Then, the aggregates, RAP, and asphalt binder were mixed thoroughly for 10–15 min. After mixing, the mixtures were again placed in the oven at 170 °C for 4 h to simulate the short-term aging and ensure that a suitable temperature was achieved during the compaction process. Next, the mixtures were transferred to the steel mold shown in Figure 2a, which had dimensions of 50 × 50 × 5 cm (width × length × thickness). Finally, the mixtures in the mold were quickly compacted by a vibratory plate compactor, shown in Figure 2b, to achieve a 5 cm thick slab. The compacted mixtures were left in the mold overnight (12 h) before demolding (Figure 2c).

Figure 2. The specimen preparation steps: (**a**) pouring the mixture into a mold and (**b**) compaction. (**c**) The specimen following simulation using the three-wheel polishing device.

2.2.6. Simulation of Asphalt Surface Abrasion

The skid resistance of road surfaces at an early age (after construction) and during operations is used as a safety indicator by many road authorities worldwide. The initial skid resistance of the road surface should be higher than that required by the design guidelines to ensure sufficient braking distances [43]. In general, the skid resistance of the road surface decreases with increased road service lifetimes and many passing vehicles. Research by NCAT (2006) [29] has revealed that the skid resistance of the road surface reduced to their minimum values and kept constant throughout their service lifetimes. The minimum skid values were usually observed from the road surface after so many thousands of vehicles had driven over it. However, these skid resistances were usually measured only in situ. It will be very useful for road authorities if the skid resistances of asphalt–concrete can be estimated during the mixture design period. Accordingly, the NCAT developed the TWPD for simulating the abrasion actions between vehicle tires and the road surface. The abrasion simulation was used to investigate the wearing characteristics of an asphalt surface in the field, and it can be completed in less than two weeks. The TWPD developed by NCAT was used as the prototype for TWPD manufactured in this research (Figure 3).

Figure 3. The three-wheel polishing device (TWPD).

The TWPD consists of three wheels with pneumatic tires. The wheels have a diameter and thickness equivalent to 20.32 and 7.62 cm, respectively. The wheels were fixed to ball bearings and attached to circular steel plates, which the motor can rotate at various constant speeds. During the abrasion simulation, water was sprayed simultaneously on the asphalt slab while the three wheels ran over the specimen surface (5.59×10^{-6} m^3/min). The running path of the three wheels was created, with a diameter of 28 cm. This polished path coincides with the skid resistance measurement region of the dynamic friction tester (DFT), which will be explained in the next section.

To conduct the abrasion simulation in this research, the asphalt slab was installed in the TWPD chamber (Figure 4a). After that, the three wheels were lowered to contact the slab surface. Then, the three wheels were driven on the slab surface while the water was continually sprayed to prevent overheating during abrasion. The abrasive action simulated by the TWPD was performed at 100 revolutions per minute (rpm). The asphalt slabs were polished by the three wheels until 100,000 cycles of polishing were complete (Figure 4b). Two replicate specimens per mixture were prepared and polished by the TWPD.

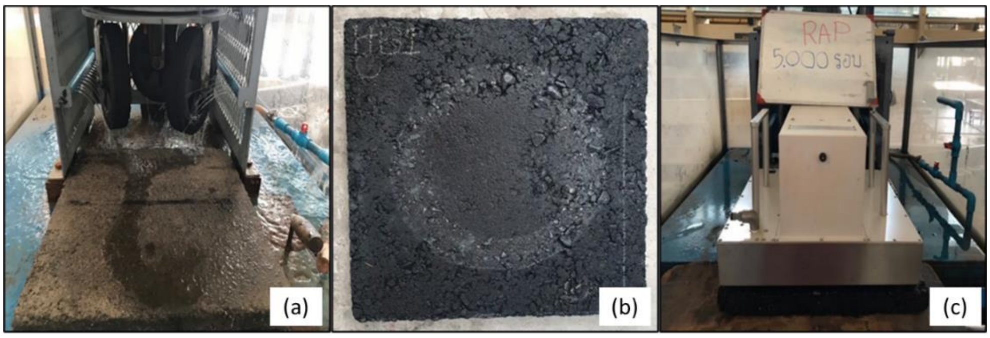

Figure 4. (**a**) Slab installed in the TWPD chamber, (**b**) the asphalt slab after polishing by the TWPD, and (**c**) the skid resistance measurement.

2.2.7. Skid Resistance Measurement

The skid resistance of the polished slab was measured using the DFT according to ASTM E1911 [44]. The DFT was placed on the slab surface for skid resistance measurement before polishing, at 5000, 10,000, 25,000, 50,000, and 100,000 cycles of polishing (see Figure 4c). The slab was marked to locate the same position of DFT measurement on each slab. Before the skid resistance measurement, the slab surface was left to dry for 30–45 min at room temperature. Accordingly, the initial skid resistance and skid resistances after the consecutive polishing cycles were determined. These measured skid resistances will be correlated with the asphalt properties, aggregate properties, and aggregate gradation in the following sections.

3. Results and Discussion

3.1. Material Properties

3.1.1. The Engineering Properties and Chemical Composition of the Aggregates

Table 6 presents the engineering properties of aged and virgin aggregates. The PSV (Initial) and PSV (Final) are the PSV of test aggregates before and after polishing, respectively. Higher values of PSV and LAA indicate lower abrasion resistance. Similarly, a rise in AIV and ACV represents a drop in the strength of the tested aggregates. Table 6 reveals that the engineering properties of the aged aggregates are not substantially different from the properties of the virgin aggregates.

Table 6. The engineering properties of aged and virgin aggregates.

Properties Test	Virgin Aggregates	RAP Aggregates	Specification
AIV (%)	22.5	19.7	<25
ACV (%)	21.0	21.7	<25
LAA (%)	24.4	29.6	≤40
PSV(Initial)	54.0	52.0	-
PSV(Final)	35.0	37.0	

The XRD analysis shown in Figure 5 demonstrates that the main chemical composition of the aged and virgin aggregates is calcium oxide (CaO). Moreover, the same minor chemical components were observed from both the aged and virgin aggregates; these chemical compositions are calcium carbonate ($CaCO_3$), magnesium (Mg), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and sodium oxide (Na_2O). It can be concluded from the XRD analysis that the aged and virgin aggregates used in this research are limestones with the same secondary mineral components. This may be why the properties of the aggregates were similar, as shown in Table 5. It should be highlighted that the aged aggregates were extracted from 5-year-old RAP.

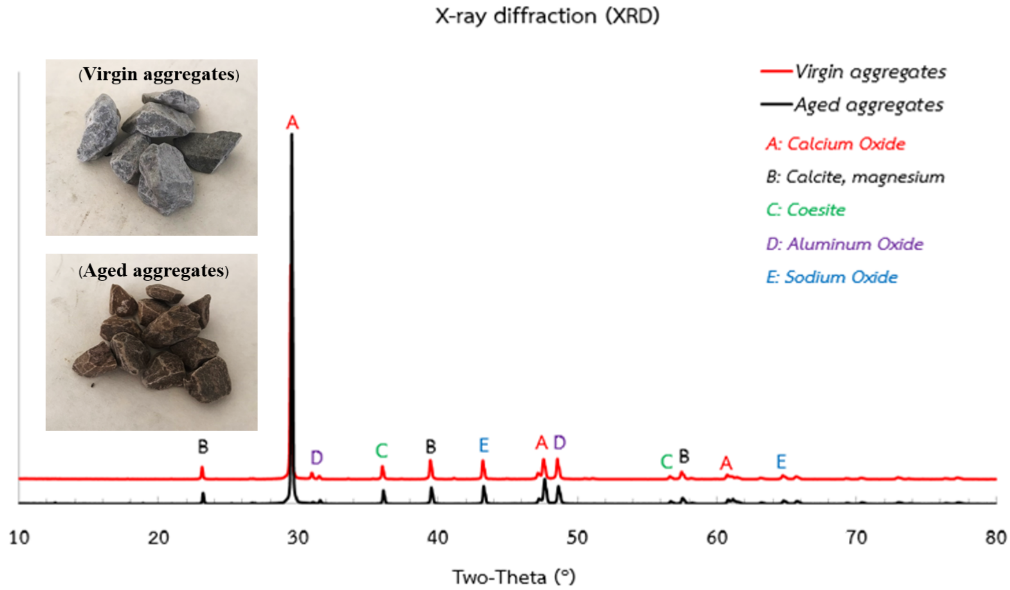

Figure 5. The XRD spectra of aged and virgin aggregates.

3.1.2. Asphalt Binder Properties

The penetration, softening point, and ductility of the virgin and aged asphalt binder are presented in Table 7. Similar to the results obtained from previous research, the penetration and ductility of the aged asphalt dropped significantly due to the irreversible oxidation process in the field [10,45]. This resulted in the stiffer responses of the aged asphalt compared to the virgin asphalt. However, the softening point of the aged asphalt was found to be higher than that of the virgin asphalt.

Table 7. The asphalt binder properties.

Properties Test	Virgin Asphalt	Aged Asphalt	Specification (AC 60/70)
Penetration (dmm.)	66.5	3.0	60–70
Softening Point (°C)	40.7	75.3	45–55
Ductility (°C)	>100	1.8	≥40

3.2. Skid Resistance

Figure 6 illustrates the relationship between the skid resistances measured at 20 kph (DFT20) of DFT disk speed and the number of cycles. The DFT20 was selected to be converted to the International Friction Index (IFI) [46]; therefore, it was used to represent the skid resistance of asphalt mixtures in this research. Figure 6 shows that the initial skid resistance ($DFT_{Initial}$) of the mixture with 100% virgin aggregates (V100) was the highest, followed by the mixtures of virgin and aged aggregates (CV50:FR50 and CR50:FV50). The R100 mixture provided the lowest $DFT_{Initial}$. The skid resistance of all the test slabs was significantly reduced during the first and the 10,000th polishing cycles. The decrease in skid resistance decreased after 10,000 cycles and remained constant when the polishing cycle was greater than 20,000. The constant skid resistances after 20,000 cycles are referred to as the final skid resistance (DFT_{Final}).

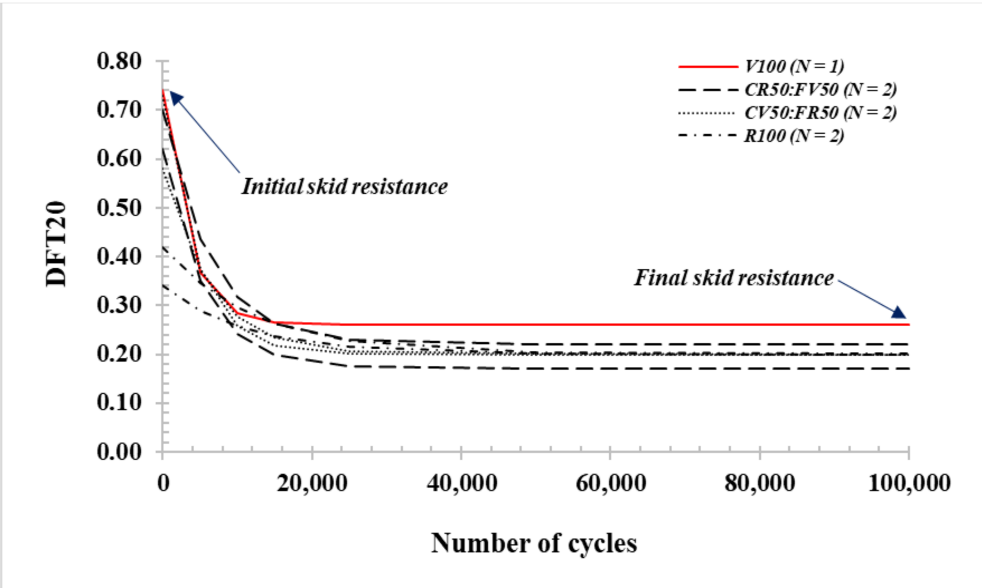

Figure 6. The relationship between the skid resistance measured at 20 kph and the number of cycles.

3.2.1. The Influence of the Asphalt Binder on the Skid Resistance

The amount of asphalt and asphalt properties affect the skid resistance of the asphalt–concrete [47]. The asphalt content of all the mixtures characterized in this research was 5%; accordingly, the influence of asphalt content was neglected from the correlation analysis. To investigate the effects of the proportion of aged asphalt on the skid resistance, Equations (1)–(3) were used to estimate the properties of the blended asphalt binder [11].

$$(a + b) \log(pen_{mix}) = a \times \log(pen_1) + b \times \log(pen_2) \quad (1)$$

where pen_{mix} is the calculated penetration of the blended asphalt, pen_1 is the penetration of aged asphalt, pen_2 is the penetration of virgin asphalt, and a and b are the proportion of aged asphalt (a) and virgin asphalt (b): $a + b = 1$.

$$T_{R\&BMix} = a \times T_{R\&B1} + b \times T_{R\&B2} \quad (2)$$

where $T_{R\&BMix}$ is the calculated softening point of blended asphalt, $T_{R\&B1}$ is the softening point of aged asphalt, $T_{R\&B2}$ is the softening point of virgin asphalt, and a and b are the proportion of aged asphalt (a) and virgin asphalt (b): $a + b = 1$.

$$(a + b) \log(duc_{mix}) = a \times \log(duc_1) + b \times \log(duc_2) \quad (3)$$

where duc_{mix} is the calculated ductility of the blended asphalt, duc_1 is the ductility of the aged asphalt, duc_2 is the ductility of the virgin asphalt, and a and b are the proportions of the aged asphalt (a) and virgin asphalt (b): $a + b = 1$.

Figure 7 shows the relationship between the skid resistance of recycled hot mix asphalt and the properties of the blended asphalt. The figure shows that the skid resistances of recycled hot mix asphalt strongly correlated with the penetration, softening, and ductility values of blended asphalt (R^2 is 0.72–0.88). It also indicates that an increase in the amount of virgin asphalt in the blending led to the rise in $DFT_{Initial}$. The higher proportion of aged asphalt reduced the $DFT_{Initial}$ of the asphalt slabs since the surface of the test specimen was covered by hard, stiff, and slippery materials when it is wet. In contrast, it can be observed from Figure 7 that the increases in aged asphalt amount resulted in minor changes in the final skid resistance (DFT_{Final}). Therefore, the properties of the blended asphalt had only a small effect on the DFT_{Final}.

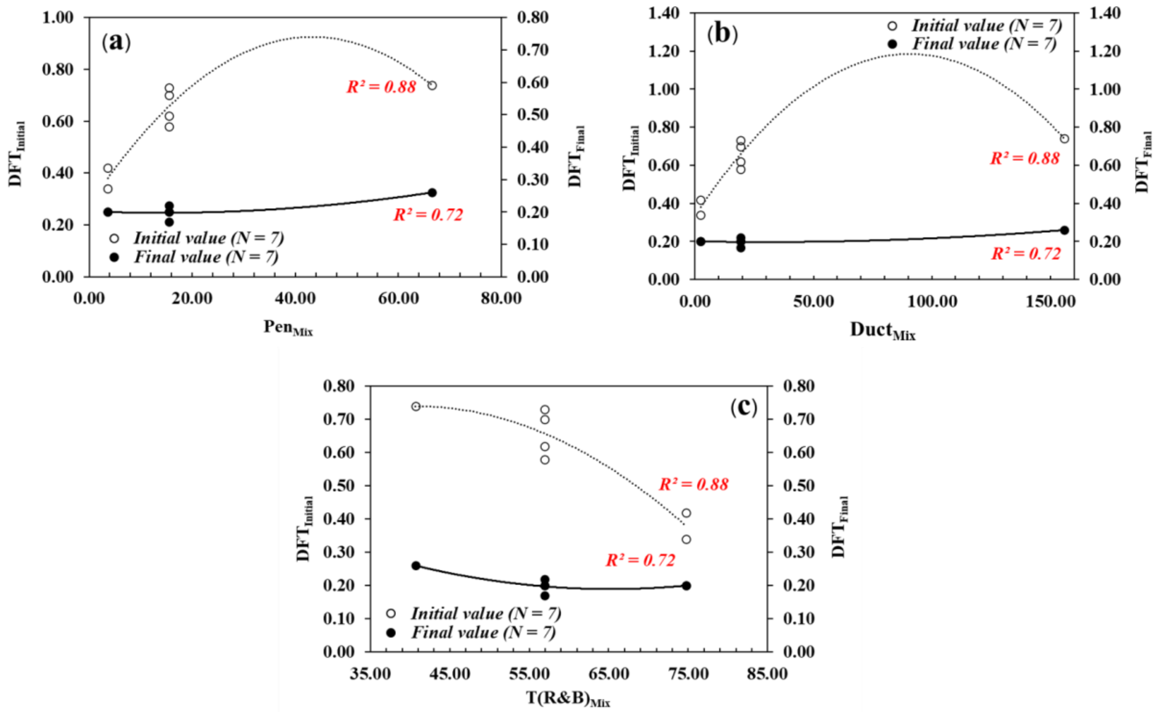

Figure 7. The relationship between the initial and final skid resistances and (**a**) the penetration values, (**b**) the softening values, and (**c**) the ductility values.

3.2.2. The Influence of the Engineering Properties of Aggregates on the Skid Resistance

Aggregates with high abrasion resistance are the most desired aggregates for the asphalt–concrete with high friction because the aggregates with high PSV are assumed to provide greater skid resistance values [47]. However, previous research has demonstrated that the skid resistance of hot mix asphalt depends on many factors, including the asphalt binder, aggregates, climate, vehicle, and construction techniques. Therefore, other influencing factors should be considered since the skid resistance of asphalt–concrete does not depend only on the PSV values [47] but also on strength and abrasion resistance of aggregates. Figure 8 illustrates the relationship between the skid resistances of recycled hot mix asphalt and the engineering properties of aggregates. Figure 8 showed that low values of R^2 were obtained from the correlation analysis between skid resistance and aggregate properties (R^2 = 0.19–0.31). The small differences in the engineering properties of the aged and virgin aggregates may be the cause of these low correlations. Therefore, the changes in skid resistance of recycled hot mix asphalt in this research were predominantly due to other factors.

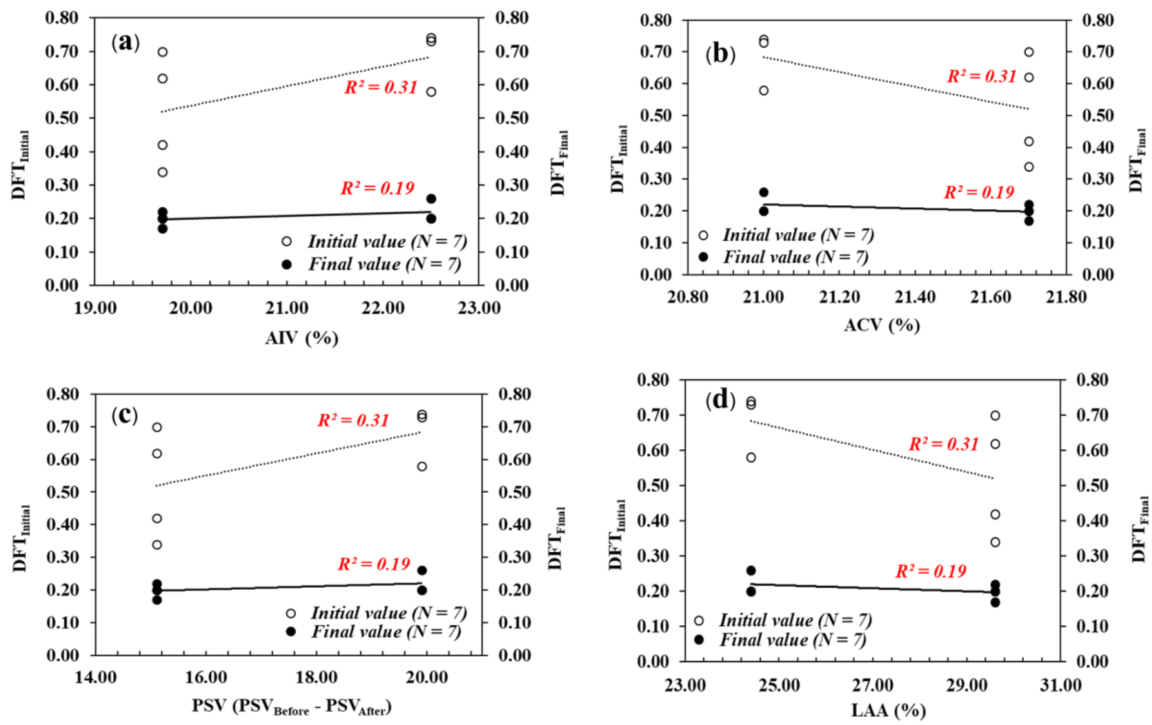

Figure 8. The relationship between the initial and final skid resistances and (**a**) the AIV, (**b**) the ACV, (**c**) the PSV, and (**d**) the LAA values.

3.2.3. The Influence of Aggregate Gradation on the Skid Resistance

In general, the particle size and gradation of the aggregates affect the skid resistance of asphalt–concrete. The decreases in the size of the aggregates may result in increases in the skid resistance of asphalt mixtures. This is partly due to the influence of the fine aggregates, which control the micro-texture formation on the asphalt–concrete surface [47].

Previous research has revealed that aggregate gradation is the significant factor affecting the skid resistance of asphalt–concrete. Moreover, the aggregate gradation of asphalt–concrete fits well with the Weibull distribution function [48]. The curve-fitting parameters in Equation (4), λ and κ, can represent the gradation parameters.

$$F(\chi, \lambda, \kappa) = 1 - e^{-\left(\frac{\chi}{\lambda}\right)^{\kappa}} \quad (4)$$

in which χ is the aggregate size in mm, λ is the shape parameter, and κ is the scale parameter. These two parameters vary according to the particle size distribution or the gradation of the mixture. Table 8 presents the Weibull model parameters of the four mixture gradations. Figure 9 illustrates an example of the Weibull curve-fitting with the aggregate gradation of hot mix asphalt (V100).

Table 8. Gradation parameters of the four mixtures.

No.	Mix Design	λ	κ	R^2
1.	V100 (CV50:FV50)	6.092	0.804	0.99
2.	CR50:FV50	5.430	0.885	0.99
3.	CV50:FR50	7.760	0.770	0.97
4.	R100 (CR50:FR50)	5.697	0.806	0.99

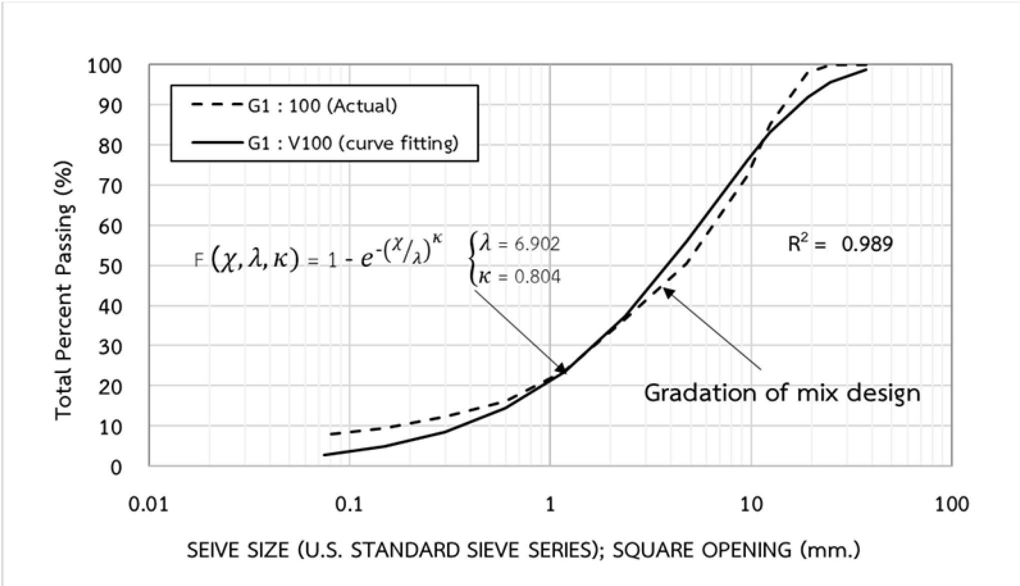

Figure 9. Comparison between the experimentally measured gradation of the V100 mixture and the fit of the gradation to the Weibull distribution function.

Figure 10 shows the correlation between the skid resistances of recycled hot mix asphalt and the gradation parameters obtained from curve-fitting with the Weibull distribution function.

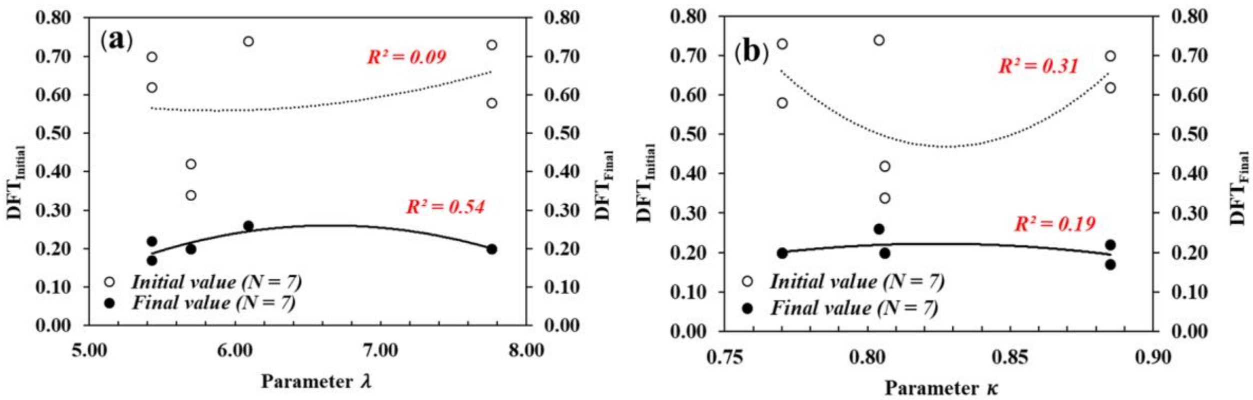

Figure 10. The relationship between the initial and final skid resistance and the aggregate gradation parameters: (**a**) the λ parameter and (**b**) the κ parameter.

The scale parameter, κ, was found to have a low correlation with recycled hot mix asphalt skid resistance, as illustrated by Figure 10b. However, the λ parameter was found to have a moderate correlation (R^2 = 0.54) with the DFT_{Final}. This correlation means that the DFT_{Final} depends on the aggregate gradation but not the $DFT_{Initial}$. However, the increases in the λ parameter caused only small changes to DFT_{Final}.

In summary, there is a correlation between the skid resistance of recycled hot mix asphalt, the asphalt binder properties, and the aggregate gradation, as illustrated in Figure 11. The properties of the blended asphalt binder strongly influenced the $DFT_{Initial}$. The increases in the amount of virgin asphalt binder in the blended asphalt resulted in increased penetration and ductility values, which also enhanced the $DFT_{Initial}$ of the mixtures. The DFT_{Final} was found to have a good correlation with the asphalt properties and a moderate correlation with the gradation parameters. As shown in Figure 11, the asphalt properties and aggregate gradation altered the characteristics of DFT_{Final}, since the asphalt binder was partly polished from the asphalt surface. However, the combined effects of the asphalt properties and the gradation contributed only a small variation in DFT_{Final}.

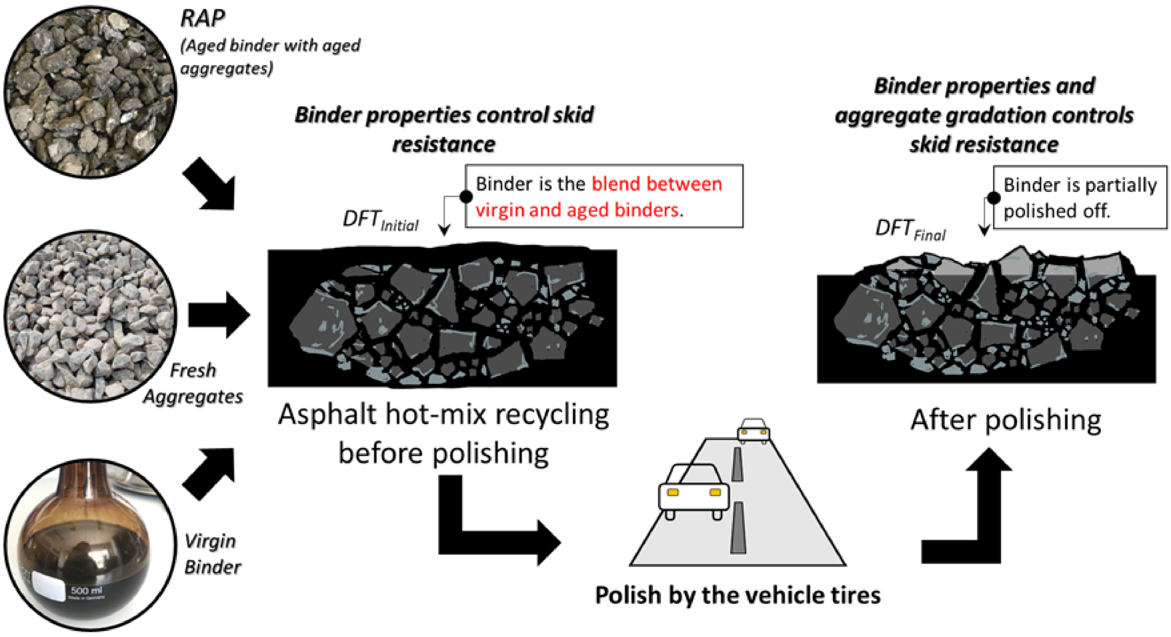

Figure 11. Graphical illustration of the research findings.

4. Conclusions

This research aimed to identify the influences of aged asphalt and aggregate properties on the skid resistance of recycled hot mix asphalt. The aged asphalt and aged aggregate were carefully extracted from RAP for an in-depth examination. The mechanical properties and engineering performances of the aged asphalt, virgin asphalt, aged aggregates, and virgin aggregates were correlated with the skid resistances of laboratory-prepared specimens. The TWPD was used to simulate the deterioration of the asphalt surface in the field, which is mainly caused by the abrasive action between vehicle tyres and the asphalt surface. Accordingly, decreases in asphalt skid resistance can be measured, characterized, and correlated with the asphalt binder and aggregate properties. The initial skid resistances were measured from the asphalt surface before the simulation. The final skid resistances were determined from the asphalt surface after 100,000 cycles of polishing. The findings from this research can be summarized as follows.

- This research determined the engineering properties and chemical compositions of virgin and aged aggregates and compared. Both aggregates' mechanical and engineering properties (AIC, ACV, PSV, and LAA) were very similar. The XRD results indicated that the main chemical component of both aggregates is CaO; accordingly, limestone is the rock type used for both virgin and aged aggregates in this research.
- In agreement with previous research, the aged asphalt has lower penetration and ductility values than the virgin asphalt. The softening point of the aged asphalt is, however, greater than that of the virgin asphalt. Therefore, the aged asphalt is stiffer than the virgin asphalt due to irreversible oxidation.
- While the amount of asphalt binders was kept at 5% by aggregate mass, the proportion of aged aggregates to virgin aggregates was maintained at 50:50 for all the mixtures. The initial and final skid resistances of recycled hot mix asphalt are strongly correlated with the engineering properties of the blended asphalt binder. These findings were summarized from the high values of the coefficient of determination (R^2 is equivalent to 0.72–0.88) obtained from the regression analysis. The increases in the penetration and ductility of the blended asphalt resulted from the rise in the amount of virgin asphalt in the mixture. They led to an increase in the initial skid resistance of recycled

hot mix asphalt. However, the changes in the properties of the blended asphalt did not contribute much to the final skid resistances. Properties of the blended asphalt have little influence on the final skid resistance.

- The skid resistance of recycled hot mix asphalt, both initial and final values, displays no correlation with the properties of the aggregate (R^2 values equivalent to 0.19–0.31). The small differences in aggregate properties may cause the low R^2 values obtained in this research.
- The λ and κ parameters from the Weibull distribution were used to represent the gradation characteristics of the asphalt aggregates. The low correlation between the skid resistance and the κ parameter was observed from the regression analysis. However, a moderate correlation (R^2 = 0.54) was obtained between the final skid resistance and the λ parameter.
- The results illustrate that the initial skid resistance of recycled hot mix asphalt was strongly influenced by the properties of the blended asphalt binder. In contrast, the final skid resistances depended on the asphalt binder properties and the recycled hot mix asphalt gradation. This can be explained by the characteristics of the asphalt–concrete surface after polishing. The vehicle abrasion partially stripped off the asphalt binder covered on the aggregate surface; therefore, the aggregate asperity was exposed and partly controlled the final skid resistances.

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