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UNSATURATED POLYESTER (UP) RESIN MIXED WITH AGGREGATES AS THE SURFACE COURSE FOR PERMEABLE PAVEMENTS

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Abstract: In this study, unsaturated polyester (UP) resin was used as the adhesive material for blending with alabaster or natural aggregate at ambient temperature for the surface course on pavements. UP resin is non-toxic and has good weather resistance. It is a good material for replacing the commonly seen epoxy resin. The mixture after blending UP resin with alabaster or natural aggregates has a very high strength and its stability can reach two to three times of that of asphalt mixture within a few hours. Moreover, the mixture's coefficient of permeability is nearly 40 times higher than that of porous asphalt mixture. In this study, the effects of temperature and water content of aggregates on the hardening of UP resin mixture were studied. We found that different additions of accelerator and hardener were required at different temperatures to adjust the hardening time of mixture. Higher additions resulted in faster hardening rate, but adding an excessive amount reduced the final strength of the mixture instead because of the residues of the accelerator and hardener. The water content of aggregates caused the hardening reaction to be sluggish and incomplete. Only 1% of water content in aggregates substantially slowed down the hardening. Conditions at higher temperatures reduced the effect of water on hardening.

1 INTRODUCTION

There has been a need to ease the regional drainage burden resulting from instantaneous heavy rainfall and the heat island effect in urban areas in recent years, as well as a need to reduce the thermal energy, carbon emissions, and costs incurred during paving by the asphalt industry. Meanwhile, there has also been a desire to provide landscape environments that are beautiful and culturally innovative. Hence, the promotion of permeable pavement is currently in full swing. In this study, unsaturated polyester (UP) resin was selected as the adhesive material for blending with alabaster or natural aggregates under ambient temperature for a surface course on pavements. The color pigments thus can be added to the mixture to create beautiful and culturally innovative landscape environments. The surface course can be laid out on a permeable pavement for pedestrian pathways and bicycle lanes. The surface water can be permeated, conserved, and slowly drained through the surface course during a certain period. This innovative structure thus enables road permeation and water conservation and obviates the need for building a huge drainage system considering the disappearance of surface vegetation within the urban areas. Its use is in line with the "On-site Water Retention Indicators" for green building, high-performance green building material for water permeability, recyclable green building material, and the eco-city policy that have recently been promoted by the Taiwan government. In this study, the effects of temperature and water content of aggregates on the hardening of UP resin mixture were studied in depth.

2 THE UP RESIN IN THIS STUDY

UP resin is not toxic and has good weather resistance (Lee and Han 1987, Lem and Han 1984). It is a good material for replacing the commonly seen epoxy resin (Daid et al. 1985, Fowler and Kukacka 1981, Manson 1990). As shown by relevant literature (Spiecker et al. 2003), the strength and wear resistance of the mixture obtained by blending UP resin with aggregates after addition of accelerator and hardener performs very well. The blending process can be performed at room temperature, unlike the blending of asphalt mixture, which needs temperatures exceeding 120°C. UP resin has excellent adhesive force and the contact area between coarse aggregates within mixture can be increased without more mineral aggregates. Meanwhile, the strength of UP resin mixture is acceptable despite the presence of many internal voids, so the drainage effect of mixture is extremely good. However, many factors affect the hardening of UP resin mixture, including the composition of the resin, the additions of accelerator and hardener, the hardening temperature, and the hardening time. The UP resin of ETERSET 2519P-S type suitable for resin concrete provided by Eternal Materials Co., Ltd. was used in this study. Its characteristics include medium-to-high viscosity, prepromoted setting, good flexural strength and compressive strength, good surface dryness, and low shrinkage rates (Pusatcioglu et al. 1979) (as shown in Table 1).

Table 1: Basic characteristics of UP resin used in this study

Appearance	Purple-red opaque
Styrene monomer content (%)	38-41
Viscosity - Brookfield at 25°C, spindle #3, 60 rpm (cps)	500-600
Acid value (mg KOH/g resin)	14-22
Specific gravity	1.1-1.16

Pure-resin hardening characteristics: Room-temperature hardening at 25°C, 1.0% Hardener (55% Methyl Ethyl Ketone Peroxide (MEKPO) included)

Gelation time (min)	10-13
Minimum hardening time (min)	15-30
Peak exotherm (°C)	165-200
Physical properties of the hardened injection molding product	Transparent injection molding product, ETERSET 2519P-S
Barcol (934-1) hardness	50
Tensile strength (kgf/mm^2, ASTM D 638)	6.5
Elongation rate (%, ASTM D 638)	3.5
Flexural strength (kg/mm^2, ASTM D 790)	13
Flexural modulus (kg/mm^2, ASTM D 790)	375
Heat distortion temperature (°C, ASTM D 648)	93
Water absorption rate (%, JIS K6919)	0.18

3 UP RESIN BLENDING TEST

3.1 Gradation of Natural Aggregates

The gradation of natural aggregates was adjusted based on the gradation of porous asphalt mixture. We used 20% of 19.0 mm (3/4 in) aggregate, 35% of 9.5 mm (3/8 in) aggregate, 30% of 6.35 mm (1/4 in) aggregate, and 15% of sand. Because the resin is easily absorbed by fine aggregates such as mineral filler to sequentially reduce its adhesive force, the mineral filler was not used in the gradation. The gradation for natural aggregates is shown in Table 2.

Table 2: Gradation for natural aggregates

Aggregates Sieve size (in)	19.0 mm (3/4 in)	9.5 mm (3/8 in)	6.35 mm (1/4 in)	Sand	Mineral filler	Amount of Usage
1.5	100	100	100	100	100	100.00
1.0	100	100	100	100	100	100.00
0.75	79	100	100	100	100	95.80
0.5	1	68	100	100	100	69.00
0.375	0	29	100	100	100	55.15
No. 4	0	1	51	99	100	30.50
No. 8	0	0	9	80	100	14.70
No. 16	0	0	4	51	100	8.85
No. 30	0	0	2	26	100	4.50
No. 50	0	0	2	7	100	1.65
No. 100	0	0	1	7	99	1.35
No. 200	0	0.1	0.9	2.8	88.4	0.73
Ratio of Usage (%)	20	35	30	15	0	

3.2 Compacted UP Mixtures Test

The 3.175 mm (1/8 in) alabaster (single aggregate), 3.81 mm (1.2/8 in) alabaster (single aggregate), and natural aggregate (gradation in Table 2) were used to respectively prepare the 4-in specimens of compacted UP mixtures. Figure 1 shows the dry alabaster. The UP resin content includes 4.5%, 5.0%, and 5.5%. The specimens and test data are listed in Table 3.

Figure 1: Dry alabaster

In Table 3, the bulk specific gravity of 3.175 mm (1/8 in) alabaster and 3.81 mm (1.2/8 in) alabaster specimens decreased because of the increase in resin content, whereas the change in resin content did not significantly affect the bulk specific gravity of the natural aggregate specimen. Moreover, the water absorption test indicates that the water absorption rate of 3.175 mm (1/8 in) alabaster specimen is directly proportional to the resin content, whereas the natural aggregate specimens had a lower water absorption rate despite the increasing resin content. In addition, the Marshall indoor permeameter was used in the study to measure the specimens' water permeability rate (ml/sec), which was converted into the coefficient of permeability (k, cm/sec). The k values lie between 0.137 cm/sec and 0.365 cm/sec. According to the coefficient of permeability for permeable concrete paving blocks specified in Chinese National Standards (CNS) 14995, the k value should be greater than 1.0 × 10−2 cm/sec. The k values of UP resin mixture specimens were nearly 40 times this standard, with the 3.81 mm (1.2/8 in) alabaster specimens showing the best values and the natural aggregate specimens showing the worst. This is probably because the fewer voids in the gradation of natural aggregates. The content of mineral aggregates in the gradation of natural aggregates can be reduced to increase the water permeation.

Table 3: Specimens and test data

Aggregate type	Specimen No.	UP resin content (%)	Weight in air (g)	Weight in water for saturated surface-dry specimens (g)	Weight in air for saturated surface-dry specimens (g)	Specimen thickness (mm)	Correction factor	Bulk specific gravity	Water absorption rate (%)	Water permeability rate (ml/sec)
3.175 mm (1/8 in) alabaster (single aggregate)	1	4.5	967.4	607.8	993.5	63.6	1	2.51	6.77	77.56
	2	4.5	959.8	602.7	985.3	63.6	1	2.51	6.66	81.66
	3	4.5	968.3	600.1	986.7	64.4	1	2.49	5.25	72.96
	Mean						1	2.50	6.23	77.39
3.175 mm (1/8 in) alabaster (single aggregate)	1	5.0	966.0	604.7	993.9	62.8	1	2.48	7.17	89.87
	2	5.0	965.7	594.8	983.9	62.3	1	2.46	6.16	83.17
	3	5.0	972.6	607.8	1003.3	63.7	1	2.46	7.76	89.93
	Mean						1	2.47	7.03	87.66
3.175 mm (1/8 in) alabaster (single aggregate)	1	5.5	956.8	596.7	984.5	61.6	1	2.47	7.14	75.47
	2	5.5	961.6	599.6	990.4	62.6	1	2.46	7.37	79.41
	3	5.5	959.7	596.0	986.1	63.5	1	2.46	6.77	90.80
	Mean						1	2.46	7.09	81.89
3.81 mm (1.2/8 in) alabaster (single aggregate)	1	4.5	964.8	606.3	987.7	64.3	1	2.53	6.00	96.15
	2	4.5	971.2	610.1	992.7	65.5	1	2.54	5.62	91.05
	3	4.5	960.3	601.5	985.5	65.4	1	2.50	6.56	94.28
	Mean						1	2.52	6.06	93.83
3.81 mm (1.2/8 in) alabaster (single aggregate)	1	5.0	980.0	614.1	1004.3	64.0	1	2.51	6.23	88.37
	2	5.0	966.9	608.2	991.2	63.8	1	2.52	6.34	98.62
	3	5.0	979.7	613.5	1003.2	64.9	1	2.51	6.03	82.87
	Mean						1	2.52	6.20	89.95
3.81 mm (1.2/8 in) alabaster (single aggregate)	1	5.5	974.0	609.7	998.0	63.3	1	2.51	6.18	92.82
	2	5.5	967.0	602.2	989.8	64.4	1	2.49	5.88	91.83
	3	5.5	973.1	604.6	997.3	65.4	1	2.48	6.16	88.50
	Mean						1	2.49	6.08	91.05
Natural aggregate (gradation in Table 2)	1	4.5	1027.7	609.9	1054.5	63.1	1	2.31	6.03	38.66
	2	4.5	1033.8	610.4	1061.0	65.8	1	2.29	6.04	59.74
	3	4.5	1028.0	612.5	1050.0	63.8	1	2.35	5.03	47.34

	Mean						1	2.32	5.70	48.58
Natural aggregate (gradation in Table 2)	1	5.0	1028.6	604.2	1049.3	61.6	1	2.31	4.65	38.95
	2	5.0	1032.6	610.0	1056.0	62.2	1	2.32	5.25	40.15
	3	5.0	1033.6	608.7	1055.4	62.1	1	2.31	4.88	42.31
	Mean						1	2.31	4.93	40.47
Natural aggregate (gradation in Table 2)	1	5.5	1033.9	602.0	1049.2	61.5	1	2.31	3.42	36.05
	2	5.5	1023.6	601.3	1043.0	62.4	1	2.32	4.39	32.78
	3	5.5	1033.4	605.1	1049.8	61.6	1	2.32	3.69	37.74
	Mean						1	2.32	3.83	35.52

3.2.1 Marshall Stability and Flow Tests

The strength of the UP resin mixtures was very high. Figure 2 shows the 4-in specimens of compacted UP mixtures. The specimens were not destroyed even when the Marshall stability had reached 6,000 kgf. If the loading had been continued to 8,000 kgf, the Marshall apparatus would have not been able to bear the load. The stability of asphalt mixtures are usually lower than 3,000 kgf. Evidently, the strength of UP resin mixtures far exceeds the strength of asphalt mixtures. Moreover, the flow was only 8 units (0.25 mm per unit) when the stability of the UP resin specimens exceeded 6,000 kgf, indicating that the flexibility of the UP resin mixtures is very low and that they are not prone to deformation.

Figure 2: The 4-in specimens of compacted UP mixtures

4 UP RESIN HARDENING TEST

4.1 Effect of Temperature on UP Resin Hardening

To understand the effect of temperature on the hardening of UP resin mixture, we conducted tests at lower temperatures (about 11°C to 13°C). Table 4 shows the test design and test results. The test was first attempted by adding 0.3% and 0.4% accelerator, as well as 0.8% and 1.0% hardener (the additions are relative to the UP resin's weight) to be mixed with UP resin (test design (1) in Table 4). Figure 3 shows the resulting mixture. Then, the resulting mixture blended with alabaster, as shown in Figure 4. However, the room temperature was so low that the UP resin mixture still had not hardened six hours after blending. Until the next day, it was barely thickened like jelly. The strength of mixture was still far from expectation after standing for a week. We used different additions of accelerator and hardener at lower temperature and the improvements were observed with additions of 0.5% accelerator and 1.2% hardener (test design (2) in

Table 4). Although the UP resin mixture hardened after one day, the final strength still did not reach the expectation.

Figure 3: UP resin mixed with accelerator and hardener

Figure 4: UP resin mixture blended with alabaster

We continued to conduct the combinations of 0.6% accelerator + 1.3% hardener, 0.8% accelerator + 1.5% hardener, and 1.0% accelerator + 1.7% hardener (test designs (3), (4), and (5) in Table 4). The hardening condition was better. The study was continued by increasing the UP resin content to 4.5% of the total mixture weight mixed with the combinations of 0.6% accelerator + 1.3% hardener and 0.8% accelerator + 1.5% hardener (test designs (6) and (7) in Table 4). The hardening time and the strength of mixtures were found to be good.

As proven by the test results, the UP resin is very sensitive to temperature; high temperature and low temperature drastically accelerated and slowed down the hardening rate. Adjusting the additions of accelerator and hardener reduced the effect of temperature on the hardening rate. Moreover, increasing the UP resin content allowed the mixture to be harder, resulting in a significant decrease in flow. The stability for test designs (3), (5), and (6) were greater than 5,000 kgf (11,000 pound-force). Taking considerations of the cost and required flow, the study selected test design (3) (4.0% UP resin, 0.6% accelerator, and 1.3% hardener) for the subsequent water content of aggregates test.

Table 4: Test design and test results

Test design	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Total weight of mixtures (g)	1000	1000	1000	1000	1000	1000	1000
Alabaster size (mm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81
UP resin content (% of total weight)	4.0	4.0	4.0	4.0	4.0	4.5	4.5
Accelerator content (% of resin's weight)	0.3, 0.4	0.50	0.60	0.80	1.00	0.60	0.80
Hardener content (% of resin's weight)	0.8, 1.0	1.20	1.30	1.50	1.70	1.30	1.50
Moisture content (%)	60-70	60-70	60-70	60-70	60-70	60-70	60-70
Temperature (℃)	11-13	11-13	11-13	11-13	11-13	11-13	11-13
Water content (%)	0	0	0	0	0	0	0
Color pigment	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Number of compaction	25 times (only one side)	25 times (only one side)	25 times (only one side)	25 times (only one side)	25 times (only one side)	25 times (only one side)	25 times (only one side)
Hardening time (hr)	> 24	12-15	2.0-2.5	1.5-2.0	1.5-2.0	2.0-2.5	1.5-2.0
Stability (kgf)	/	/	> 5,833	> 5,918	> 6,030	> 6,042	> 6,185
Flow (mm)	/	/	1.59	> 1.6	> 1.54	> 0.93	> 0.94
Remarks	After blending, no hardening reaction in 4-7 hr	After blending, no hardening reaction in 4-6 hr; slow hardening after 1 day	After blending, specimen can be demolded in 1.5 hr and mixture can be hardened in about 2.0-2.5 hr	After blending, specimen can be demolded in 1 hr and mixture can be hardened in about 1.5-2.0 hr	After blending, specimen can be demolded in 1 hr and mixture can be hardened in about 1.5-2.0 hr	After blending, specimen can be demolded in 1.5 hr and mixture can be hardened in about 2.0-2.5 hr	After blending, specimen can be demolded in 1 hr and mixture can be hardened in about 1.5-2.0 hr

4.2 Water Content of Aggregates Test

To understand the effects of water content of alabaster on the hardening of UP resin mixture, the study used alabasters with 0.0% (dry), 1.0%, and 1.5% of water content, along with test design (3) in Table 4 (4.0% UP resin, 0.6% accelerator, and 1.3% hardener) to measure the hardening time and final strength of UP resin mixture. The test design and the test results are shown in Table 5.

According to the test results, the specimen (UP resin mixed with water-containing alabaster) can be demolded in 1.0 hr to 1.5 hr after blending but the mixture were congealed like jelly and did not have strength. Hardening took about 2.0 hr to 2.5 hr, and the final strength was far less than that of the specimen without water-containing alabaster. With the test design (3), the stability at room temperature (21°C to 23°C) were lower than those at lower temperatures (11°C to 13°C) whether the specimens were lacked water (0% water content of aggregates) or had water content of aggregates. This again shows the high temperature sensitivity of the UP resin. In accordance with the suggestion of the resin supplier, the uses of UP resin are room temperatures of 23°C to 25°C, as well as the addition of 0.3% to 0.5% accelerator and 0.8% to 1.2% hardener. Adding a large amount of accelerator and hardener to the same UP resin content may not necessarily result in high strength in a short period; hence, the additions of accelerator and hardener at different temperatures must be adjusted accordingly.

Table 5: Water content of aggregates test and test results

Test design	(8)	(9)	(10)
Water content (%)	0.0	1.0	1.5
Total weight of mixtures (g)	1000	1000	1000
Alabaster size (mm)	3.81	3.81	3.81
Resin content (% of total weight)	4.0	4.0	4.0
Accelerator content (% of resin's weight)	0.60	0.60	0.60
Hardener content (% of resin's weight)	1.30	1.30	1.30
Moisture content (%)	64	64	64
Temperature (°C)	21-23	21-23	21-23
Color pigment	Nil	Nil	Nil
Number of compaction	25 times (only one side)	25 times (only one side)	25 times (only one side)
Hardening time (hr)	1.0-1.5	> 2	> 2.5
Stability (kgf)	3,797	2,461	2,529
Flow (mm)	1.37	0.54	0.56

5 COST ANALYSIS

Cost analysis was conducted for the mixture of alabaster and UP resin without mixed with color pigment (i.e., uncolored). The total weight of mixture was 1,000 grams (4.5% UP resin, 0.3% accelerator, and 0.8% hardener). Alabaster, UP resin, accelerator, and hardener accounted for 955 g, 44.5 g, 0.135 g, and 0.365 g, respectively. The cost of the mixture is about CAD 0.346/kg to CAD 0.390/kg. The cost of the mixture of natural aggregates and UP resin is about CAD 0.173/kg to CAD 0.195/kg. Color pigment must be stirred in to impart different colors and a beautiful appearance to the mixtures. The coloring effect of alabaster was better. Color pigment (1.5% with respect to resin content) was required to increases the cost by CAD 0.005/kg to CAD 0.013/kg. Coloring of natural aggregates was more difficult. More color pigment (about 25% with respect to resin content) was required, thus increasing the cost by CAD 0.072/kg to CAD 0.234/kg. Table 6 shows the cost comparison for the alabaster and natural aggregates.

Table 6: Cost comparison of alabaster and natural aggregates

	Alabaster	Natural aggregates
Aggregate (CAD/kg)	0.238	0.017
UP resin (CAD/kg)	2.598 - 3.031	
Color pigment (CAD/kg)	6.495 - 21.649 (varies with the color)	
Accelerator and hardener (CAD/kg)	8.660 - 12.990	

6 CONCLUSIONS

UP resin after blending with alabaster or natural aggregates has very high strength. It can immediately present stability two to three times than that of asphalt mixtures in a few hours, and even have coefficient of permeability (k) nearly 40 times than that of porous asphalt mixture. We used alabaster because it can be colored easily and it can be laid out on an environment with landscape requirements, such as pedestrian pathways and bicycle lanes. Because the aggregates adhered through the UP resin, the resin and asphalt are equally subject to the problem of aging. Moreover, the resin price is higher than that of asphalt. We can adopt natural aggregates with less mineral aggregates to reduce the cost and maintain their advantages of high strength and high water permeability in practice. This study obtained the following findings:

1. At different temperatures, different additions of accelerators and hardeners are needed to adjust the hardening rate of resin mixture. Higher addition resulted in faster hardening rate, and vice versa; but adding an excessive amount reduced the final strength due to the residue of accelerator and hardener. According to the resin supplier’s suggestion for room temperature (23°C to 25°C), the addition of accelerator should be from 0.3% to 0.5% and that of hardener should be from 0.8% to 1.2%. Excessively low temperature prolonged the hardening time, and excessively high temperature weakened the final strength. Tests were specifically conducted at temperature of 11°C to 13°C in the study, and the appropriate addition of accelerator is 0.6% to 1%, and that of the hardener is 1.3% to 1.7%.

2. Aggregates containing water caused the hardening reaction to be sluggish and incomplete. Only 1% of water content in aggregates had significant effects on the hardening of the mixtures. Therefore, the aggregates should be kept as dry as possible. At higher temperatures, the effect of water on hardening was reduced.

3. The strength of the mixtures originates from the mechanical properties of the UP resin itself. Even the pure UP resin without blended aggregates possessed extremely high strength; therefore, the strength of the resin mixture was less likely to be affected by the compaction process.

4. After hardening, the UP resin became hard and brittle. Adding more UP resin resulted in lower flow. Using larger and single-size aggregates can reduce the addition of resin and increase more voids, resulting in better water permeability of the road.

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