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Research Article

Experimental Investigation on the Application of Ultra-Rapid-Hardening Mortar for Rigid Small Element Pavement

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Natural stones have been typically used as a paving material in historically conserved areas due to architectural aesthetic aspect and environmental impact. However, they have been traditionally suggested in light traffic volume due to the defects caused by the increased traffic loading and volume. The failures can lead to diverse problems such as losing flatness, severe damage to both vehicles and pedestrians, high traffic congestion, maintenance cost, etc. In order to overcome these obstacles, ultra-rapid-hardening (URH) cement for rigid small element pavement (SEP) was implemented as both jointing and laying course materials. Additionally, their mechanical properties were investigated according to BS 7533-4 and National Stone Surface (NSS) in the UK. Preliminarily, the proper mix mortar design was found by comparing design parameters. The compressive and flexural strength of the joint and laying course by age was verified, and the results in early-age stage were satisfied with the requirements. The adhesive and shear strengths depending upon the width of the joint were determined, and from the test outcomes, the optimal thickness of the joint was found as 15 mm. Furthermore, by contrasting the compressive strength of the laying course with the punching shear strength, the shear strength regarding joint states was increased by up to 134.3% (fully restrained), 127.9% (semirestrained), and 107.2% (non restrained). This investigation would be possible to use as baseline data for an evaluation of the long-term performance of rigid SEP.

1. Introduction

Various types of small element pavement (SEP) (as exemplarily illustrated in Figure 1) are generally used and have been increasingly quarried in low traffic volume areas such as pedestrian zones, car parks, roads, and historic sites [1, 2]. Especially they are usually employed in historically adjacent areas or cities, owing to their architectural aesthetic and environmental impact [1, 3–5]. As the historical stone pavements are typically recommended for light traffic volume, the failures of the pavement constructions have been generated as the amount and weight of vehicles have been increased. In order to deal with heavy traffic loads, the rigid pavement which is structurally integrated among jointing material, surface element, and laying course would be considered as an alternative due to efficiency, comfortability, high-performance, and cost-effectiveness [6].

In the stone paved roads, cracks usually develop in a variety of ways, according to the cause of distress. The majority of deteriorations present to the surface layer of the pavements, particularly at the bedding and jointing bound around stone elements. Figure 2 illustrates typical failure progress of the rigid pavement. Vertical downward movement of the surface pavers created by wheel paths mostly occurs at joint mortar due to a lack of punching shear resistance between the joints and bedding. Once the surface matrix is broken down, vertical or horizontal movement of the stone elements is resultant of the crack of the substrate

(a) (b)

Figure 1: Classification of construction methods for stone element pavement. (a) Flexible surface construction (cubes). (b) Rigid surface construction (setts).

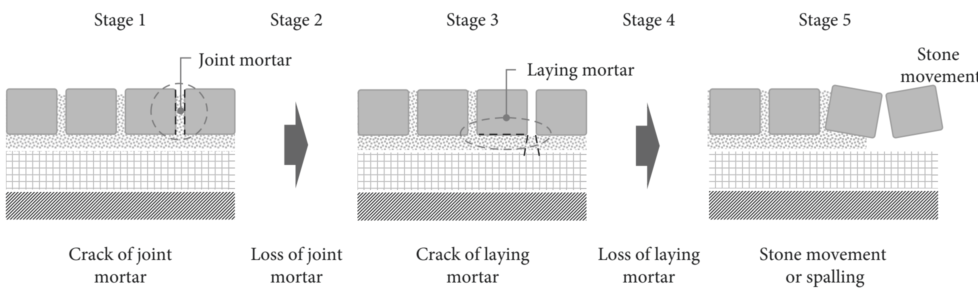


Figure 2: Damaging progress of stone pavement.

caused by high traction forces such as braking, accelerating, and cornering [7, 8]. In the final stage, the surface stones are dislodged from the pavement structure.

Because the cracks are generally developed in both laying course and the jointing material, it must consider design parameters of fine concrete such as strength, durability, interface shear strength, fluidity and cohesiveness, removal of surplus material, shrinkage of concrete, and curing time [9]. Amongst the structural properties of the mortar, the sufficient curing time that allows workers to lay out the surface layer and achieve proper strength as hardened is an essential requirement. As described in the National Stone Surfacing (NSS) from the Society of Chief Officers of Transportation in Scotland (SCOTS), the minimum requirement is approximately 4 hours in order to withstand the traffic over-riding load when the paved area may be opened.

Consequently, rapid-hardening materials with excellent mechanical strength have currently demanded both maintenance and construction of pavement. Zhang et al., for instance, adopted a microwave curing progress to epoxy mortar for rapid maintenance of concrete pavement [10]. Additionally, Guo et al. experimentally evaluated the bond strength of the rapid repair material, which was a kind of polymer-modified cementitious material, by implementing concrete patch repair [11]. Furthermore, Lee et al. [12] determined the mechanical and permeability properties of latex-modified fibre-reinforced roller-compacted rapid-hardening cement concrete, which was used for emergency repair of concrete pavements [9]. Although there are numerous studies on developing the rapid-hardening technologies and materials for the rapid repair of concrete pavements, it is unlikely to progress research implementing into the SEP.

This experimental research focused on the evaluation of ultra-rapid-hardening (URH) cement mortar as laying course and filling materials of the rigid SEP in order to investigate failure modes depending upon joint conditions and thickness of the joint and bed. Preliminarily, the optimized mix design of the laying course mortar was defined with design parameters such as initial hardening time, constructability, and settlement caused by self-weight of the surface layer. In the following tests, mechanical properties, which were compressive strength and flexural strength, adhesion, and shear resistance, were determined in accordance with the thickness and conditions of the substrate and joint.

2. Materials and Mix Design

2.1. Materials

2.1.1. Ultra-Rapid-Hardening Cement and Retardant. The URH cement and retardant employed in the study were supplied by UNION Co., Seoul, Korea. The cement is generally used in various applications such as grouting, shoe installation on the bridge, repair of concrete surface, and pipe and urgent repair. The chemical compositions and fineness of the cement and the properties of the retardant are shown in Tables 1 and 2, respectively. The cement quality

Table 1: Chemical compositions of ultra-rapid-hardening cement.

Chemical compositions (%)						Fineness (cm^2/g)
AL_2O_3	CaO	SiO_2	TiO_2	Fe_2O_3	Na_2O	
>42.0	46 ± 2.0	<5.0	<4.0	<1.0	1.5 ± 1.0	5000–7000

Table 2: Properties of retardant.

Type	Density (g/cm^3)	Particle size (μm)	pH	Solid content (%)	Color appearance
Powder	0.31	>212	7.0–8.5	95	White

was tested by Korea Quality Institute of Construction Industry according to the Korean Standard (KS) F 4044: test methods of hydraulic cement grout. Table 3 indicates the results of the test depending on the test items.

2.1.2. Fine Aggregate. The fine aggregate used for this research was sea sand provided from Jumunjin, Korea, and it has the density and water absorption of 2.59 g/cm^3 and 0.76%, respectively.

2.1.3. Natural Surface Stone (Sett). This study used the granite (quarried from Iksan, Korea), which is broadly applied for sidewalk and road pavement. The compressive strength and water absorption of the sett were determined following by the test methods of KS F 2519 and KS F 2518, respectively. The mechanical properties are shown in Table 4. They were assessed by the stone materials (KS F 2530).

2.2. Mix Design. The quality and design of laying course material are typically determined according to the weight of surface layer, construction method, constructability, and design specification. As described in NSS, the moist laying course with moist joint filling should be used in rigid pavement construction owing to preventing the segregation of materials caused by insufficient hydration.

2.2.1. Laying Course. In order to define the optimal moist mix design of the URH mortar for laying course material in the rigid pavement construction, the initial setting time, constructability, and stone settlement were considered as the design parameters. The objective elapsed time of the mortar, which was in a range of 15 min to 30 min, was preliminarily decided based on the average time when an operator laid out 10 setts in one operation. Additionally, the settlement of the surface layer aimed to be within 3 mm. Table 5 indicates mix proportions of design cases and the corresponding elapsed setting time, constructability, and settlement. Throughout the outcomes, the design case 6 was designated for the optimized moist mix design of laying course and jointing materials.

2.2.2. Joint Filling. The mix proportion of the jointing material is listed in Table 6, and the filling mortar consists of a mixture of water and the URH cement that is commonly used in pavement constructions.

3. Experimental Methods

The compressive and flexural strengths of the mortars for both void filling and bed were primarily evaluated by comparing with design recommendations from BS 7533-4 (pavement constructed with clay, natural stone, or concrete pavers) and NSS. Additionally, the structural performances such as adhesion and shear strength and punching shear strength for the joint and substrate, respectively, were examined depending on not only a various range of joint and laying course thickness but also joint conditions. It was fundamentally aimed to demonstrate failure modes of rigid SEP with URH mortar.

3.1. Compressive and Flexural Strength Tests. The basic mechanical properties of the URH mortar were investigated in accordance with the test method specified in KS L ISO 679: methods of testing cement (determination of strength). The mortar prismatic specimens with a dimension of 40 mm × 40 mm × 160 mm were prepared to test the compressive and flexural strengths of the URH mortar for laying course and joint. The compressive strength test was conducted with a load speed of 2,400 N/s using the failed specimens from the three-point flexural test. The compressive and flexural strength tests were measured at 4 hours and 3 and 28 days curing.

3.2. Adhesive Strength by a Pull-Off Test. Initial failure mode in rigid SEP normally occurs at joint interfaces due to the loss of adhesive strength resultant from lateral loads (as exemplarily shown in Figure 3(a)). Once the surface stone dislodged, the infiltration of rainwater and calcium chloride through the crack can cause decreasing durability of the mortar.

The adhesive strength of the joint filling along with the width of the joint (W) was determined in accordance with BS EN 1015-12: methods of test for mortar for masonry. Instead of the prescribed rectangular concrete panels from the guidance, the cubic natural stones with a dimension of 50 mm × 50 mm × 50 mm were adopted for the substrates in this study. The widths of joint material had a range from 10 mm to 20 mm, and the joint mortar interfaced on the top surface of the stone as illustrated in Figure 3(c). The specimens at ages of 4 hours, 3 days, and 28 days were attached to the pull-heads of test apparatus with epoxy for the pull-off test, and the specimens were pulled off with a speed of 150 N/s.

Table 3: Ultra-rapid-hardening cement quality test results.

Setting time (min)		Bleeding ratio (%)	Height change (%)		Compressive strength* (MPa)					
Initial	Terminal	3 hr	1 day	28 day	2 hr	3 hr	1 day	3 day	7 day	28 day
13	16	0.00	0.00	0.00	38.7	42.2	50.4	51.8	54.2	62.5

*Mix proportion (by mass): (Cement : water : retardant = 100 : 15 : 0.2).

Table 4: Mechanical properties of natural surface stone.

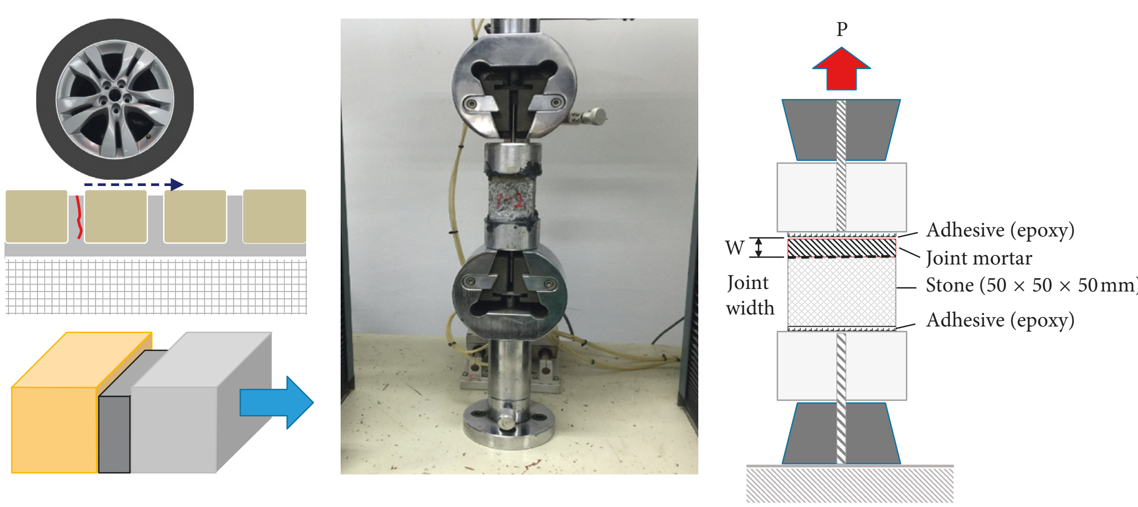
Type of stone	Compressive strength (MPa)		Water absorption (%)	
	Outcome	Acceptance	Outcome	Acceptance
Iksan	95.4	≥80	0.21	≤3

Table 5: Mix proportion and outcome of design considerations.

Design case	Mix proportion (by mass)				Setting time (min)	Constructability	Settlement
	Water	Cement	Sand	Retardant			
1	0.30			0.005	15	No good	No good
2	0.40			0.005	15	No good	No good
3	0.45	1	2.45	0.010	90	No good	No good
4	0.45			0.005	15	No good	No good
5	0.48			0.005	15	No good	OK
6	0.46			0.006	30	OK	OK

Table 6: Mix proportion of joint filling.

Mix proportion (by mass)			
Water	Cement	Sand	Retardant
0.15	1	—	0.01



(a) (b) (c)

Figure 3: Adhesive strength of joint mortar. (a) Loss of adhesive strength. (b) Testing apparatus. (c) Pull-off test setup.

3.3. Shear Strength Test. Another failure mode at joint interfaces can be made from repetitive downward or excessive loads as described in Figure 4(a). As similar to the crack mechanism of the loss of adhesive strength, the mortar can be less durable because of the environmental impact.

The shear strength test depending upon *W* was measured according to the test arrangement as indicated in Figure 4(c).

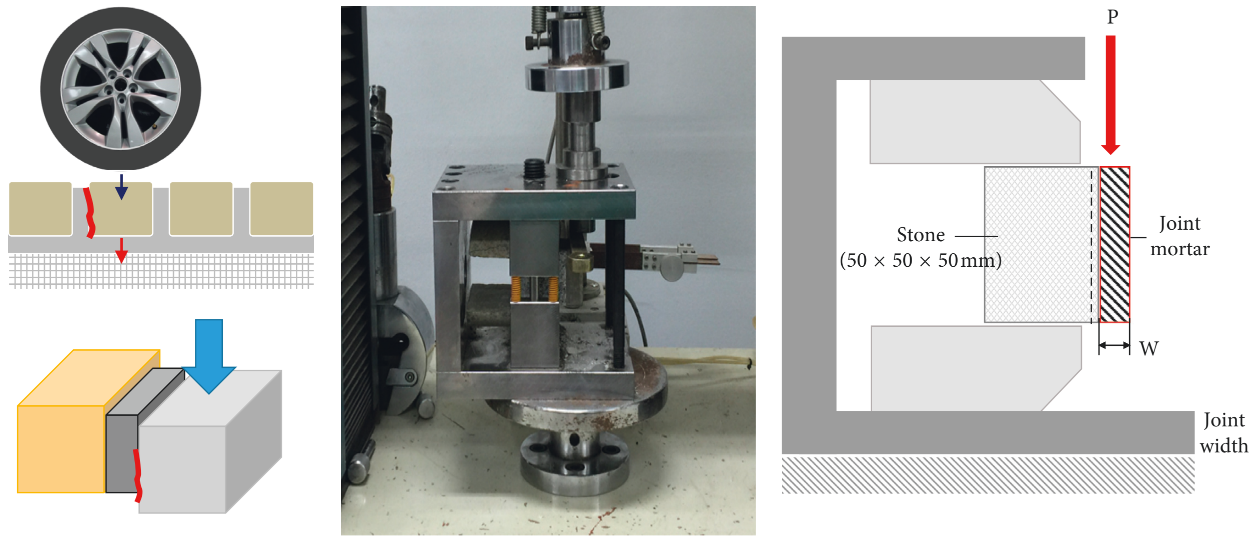


Figure 4: Shear strength of joint mortar. (a) Loss of shear strength. (b) Testing apparatus. (c) Shear strength test setup.

The substrate stones had a dimension of 50 mm × 50 mm × 50 mm, and the joint mortar was layered on the stones with different *W* ranged between 10 mm and 20 mm. The test was conducted with the prepared specimens at ages of 4 hours, 3 days, and 28 days. The load was exerted on the joint mortar with a speed of 150 N/s.

3.4. Punching Shear Test. The punching shear resistance test was intended to demonstrate the failure modes. The three different failure modes were assumed as follows: fully restrained, semirestrained, and nonrestrained surface stones as shown in Figures 5(a)–5(c), respectively. These resistance tests with the three different joint conditions above could investigate the crack patterns at the certain environment of the SEP.

The test specimens were prepared with a range of variables such as the thickness of laying mortar (*T*) and *W* as illustrated in Figure 6. The vertical load was directly exerted downward to the surface of the stone, but one more stone was stacked for both fully restrained and semirestrained conditions in order to get independent loading as indicated in Figure 6(a). The test proceeded with the specimens at ages of 3 and 28 days, and the stone was loaded with a speed of 0.06 MPa/s during the test.

4. Results and Discussion

4.1. Compressive and Flexural Strength Tests. As described in BS 7533-4 and NSS, the minimum compressive strength at 28 days is 30 MPa and 15 MPa for laying course and 40 MPa and 15–40 MPa for jointing material, respectively. Although both guidance specifies the compressive strength value, the flexural strength of jointing material at 28 days should be greater than 6 MPa, particularly in NSS. The present study primarily focused on the mix designs of mortar that satisfied with the 30 MPa and aimed 35 MPa of compressive strength for both laying course and jointing mortar as referenced from BS 7533-4 and NSS, respectively.

Figure 7 indicates the compressive and flexural strength test outcomes with regard to the laying course and joint mortar at ages of 4 hours, 3 days, and 28 days. The compressive strength of the laying course achieved the recommendation complied with the BS 7533-4 at age of 4 hours and reached 54.55 MPa at 28 days. Furthermore, its flexural strength was 7.09, 7.99, and 8.60 MPa and showed an increase along with curing periods of the mortar. In terms of the void filling mortar, the compressive strength initially developed approximately 82.6% and 110% of the design strength after 4 hours and 28 days, respectively. The early-age flexural strength achieved 7.23 MPa, which was beyond the minimum value from NSS and around 128% of its acceptance was obtained at the age of 3 days.

Throughout the outcomes, the mix design of mortar for laying course and joint almost satisfied with the qualification at 4 hours. It was found that the application of URH cement affected the increased development of early-stage strength.

4.2. Adhesive Strength by Pull-Off and Shear Strength Tests. As specified in BS 7533-4 and NSS, the minimum adhesive strength at 28 days is 1.5 MPa and 1.2 MPa for the jointing material, respectively. On the other hand, there is no particular shear strength requirement designated for vertical movement of the stone elements owing to joint detachment. The adhesive and shear strength tests at 4 hours, 3 days, and 28 days were conducted along with *W* for demonstrating initial failure modes of the URH mortar verified in the previous tests. The upper limit of *W* was decided less than 20 mm because the wheel load can directly influence the joint when having a width more than 20 mm.

Figure 8 illustrates the adhesive and shear strength test results according to different *W* values. All the adhesive strength showed far beyond both requirements even in early-age strength. Moreover, there was an increase in the strength observed as the *W* was extended. The adhesive strength of URH mortar joint at 28 days developed around

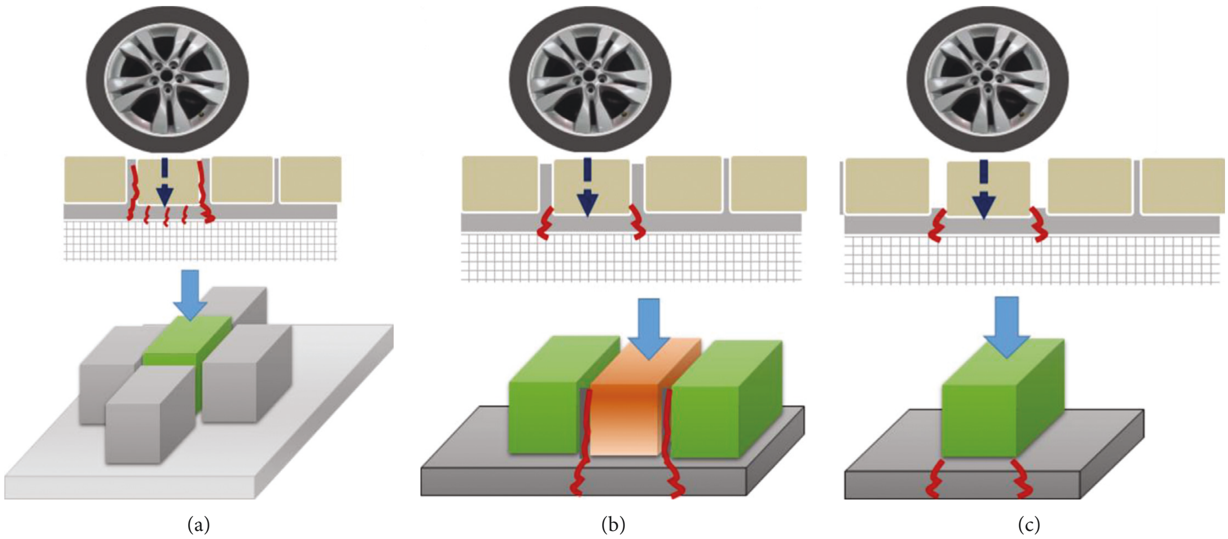


FIGURE 5: Joint conditions. (a) Fully restrained. (b) Semirestrained. (c) Nonrestrained.

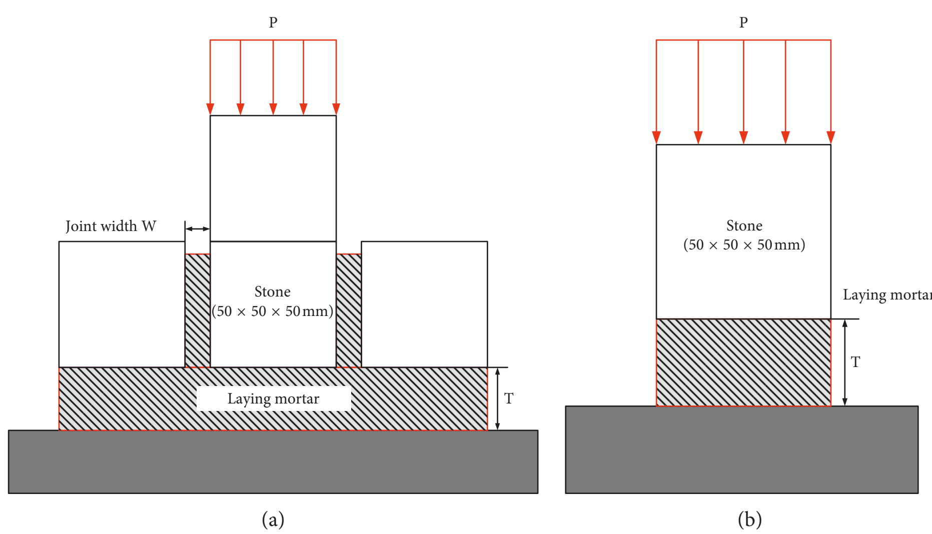


FIGURE 6: Vertical cross section of the test setup. (a) Fully restrained and semirestrained. (b) Nonrestrained.

183% (10 mm), 221% (15 mm), and 245% (20 mm) of the recommendation from BS 7533-4. As similar to the adhesive strength, the shear strength was increasingly developed as the W deepened.

Comparing with the adhesive and shear strength depending on W, it was determined that the shear strength at 28 days was less than the adhesive strength at 4 hours. Due to this consequence, it would be assumed that the failure in shear at the intervention between joint and stone surface originally occurs if the laying course was inappropriately constructed. Therefore, the fracture, cracking, and loss of joint mortar would be also progressed.

4.3. Punching Shear Test. The punching shear tests with the variables such as T and W and joint conditions were performed to define failure modes of rigid SEP. The vertical displacement was also measured during the investigations.

In the case of fully connected specimens (Figure 9(a)), the most punching shear strength in each group was developed in the specimens with $W = 15$ mm and the higher values among those were determined as 74.7 and 71.9 MPa when $T = 50$ and 25 mm, respectively, at 28 days. The specimens with $W = 10$ mm had the least shear strength values in each group excluding the one with $T = 50$ at 28 days. For semirestrained specimens (Figure 9(b)), the highest and lowest values of shear strength were obtained in the specimen groups with $W = 15$ and 10 mm, respectively. Besides, the shear strength of $T = 25$ mm ranged from 57.9 to 65.3 MPa and the spectrum of $T = 50$ mm was between 55.9 and 69.1 MPa. In spite of the shear strength of $W = 10$ mm, there were minor gaps among the values with $W = 15$ and 20 mm. In the final joint condition (Table 7), the changes in T and age of specimen affected the punching shear strength and the values were slightly increased by 0.9 and 6% in accordance with T.

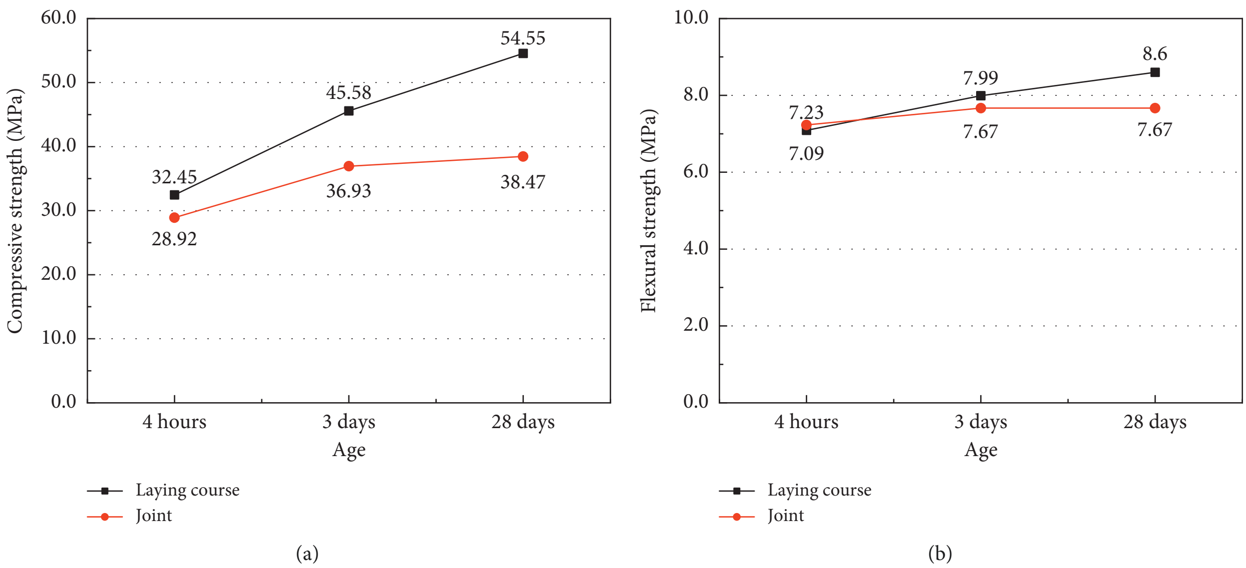


Figure 7: Test outcome of mortar. (a) Compressive strength. (b) Flexural strength.

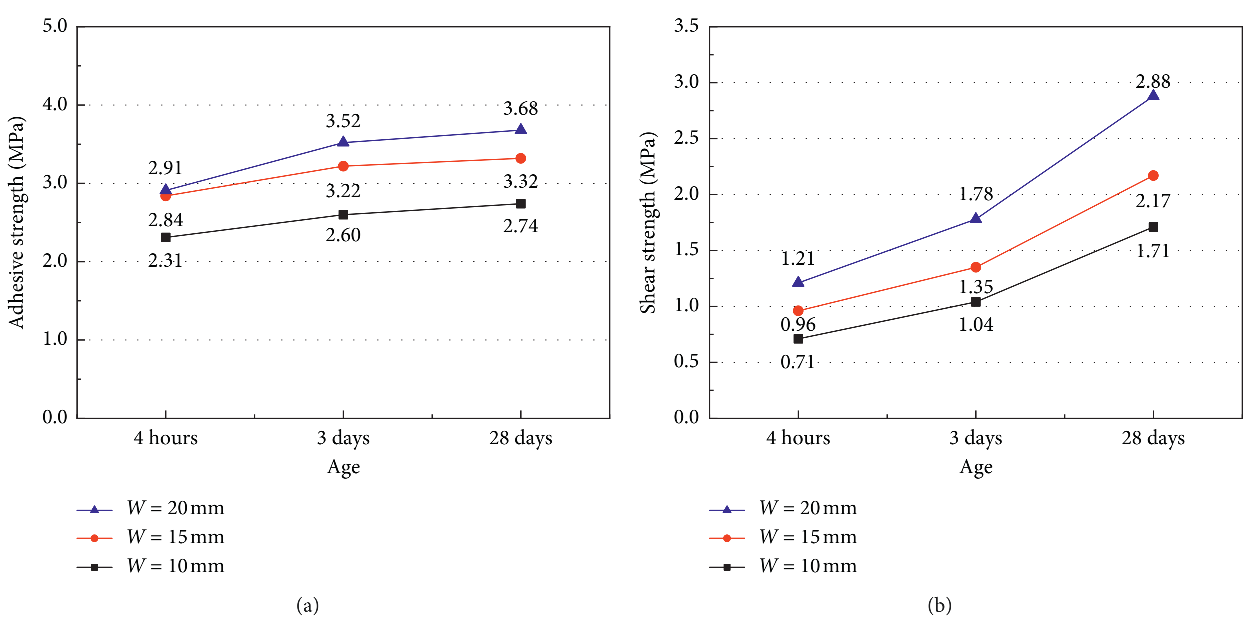


Figure 8: Test outcome of mortar. (a) Adhesive strength. (b) Shear strength.

The average compressive strength of laying course, punching shear strength with joint conditions, and those comparisons are listed in Table 8. The failure strength of fully connected and semiconnected specimens was greater than that of its laying course. On average, the enhanced failure strength of those conditions was 134.3 and 127.9%, respectively. There was a slight increase in failure strength in nonrestrained specimen compared with pure compressive strength of laying course. This would assume that the surface stone partially absorbed load from the test apparatus.

5. Conclusion

To investigate the application of URH cement for laying course and jointing materials in rigid SEP, various mechanical tests with variables were conducted, such as compressive, flexural, adhesive, shear, and punching shear tests. From the compressive strength test outcome, the early-age strength of laying course and joint was 32.45 and 28.92 MPa and satisfied with 108.2 and 82.6% of target strength, respectively. In the case of the flexural strength evaluation, the jointing material at age of 4 hours developed 120.5% of the requirement from NSS. Thus, the URH cement could be applicable as the bed and void filling materials in rigid SEP construction. In terms of the adhesive strength test result, the URH mortar for joint met BS 7533-4 recommendation of 1.5 MPa even in early-age stage. Even though the adhesive strength accomplished the requirement, the shear strength of the joint was comparably lower than the adhesive strength. Hence, the failure

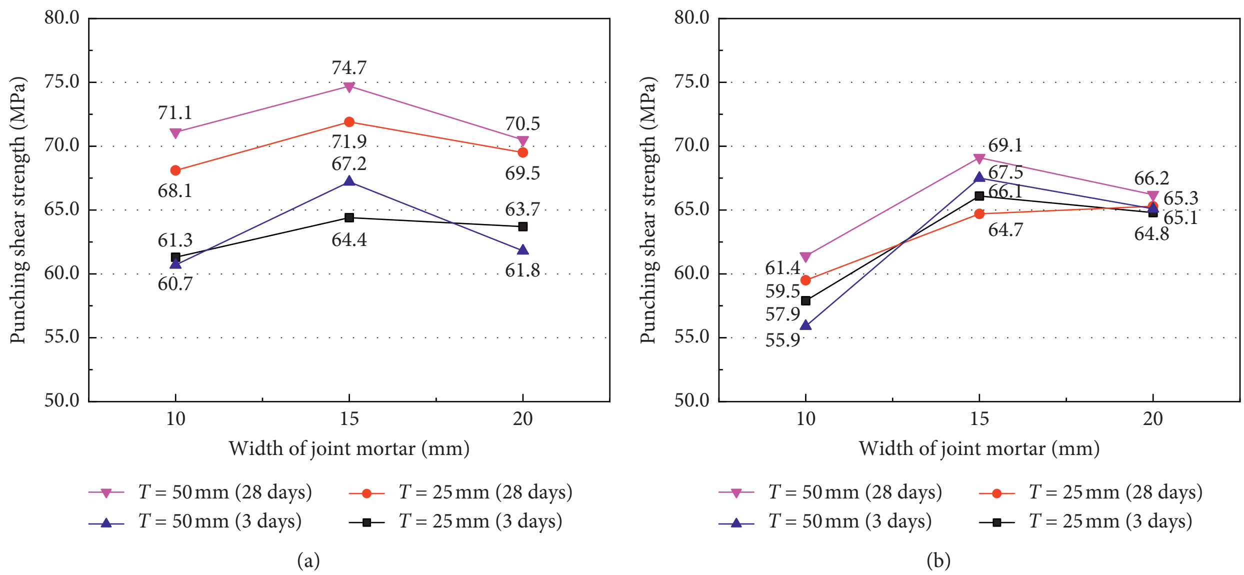


Figure 9: Test outcome of punching shear. (a) Fully restrained. (b) Semirestrained.

Table 7: Punching shear outcome of nonrestrained.

Age (Day)	*W* (mm)	*T* (mm)	Avg. punching shear strength (MPa)
3	—	25	45.8
		50	46.2
28	—	25	60.2
		50	63.8

Table 8: Mortar strength outcome and comparison.

T (mm)	*W* (mm)	Age (days)	Avg. compressive strength (MPa)	Avg. punching shear strength (MPa)			Percentage (%)		
			Laying course (*A*)	Fully (*B*)	Semi (*C*)	Non (*D*)	*B*/*A*	*C*/*A*	*D*/*A*
25	10	3	45.6	61.3	57.9		134.43	126.97	
		28	54.6	68.1	59.5	45.8 (3 days)	124.73	108.97	100.44
	15	3	45.6	64.4	66.1		141.23	144.96	
		28	54.6	71.9	64.7		131.68	118.50	
	20	3	45.6	63.7	64.8	60.2 (28 days)	139.69	142.11	110.26
		28	54.6	69.5	65.3		127.29	119.60	
50	10	3	45.6	60.7	55.9		133.11	122.59	
		28	54.6	71.1	61.4	46.2 (3 days)	130.22	112.45	101.32
	15	3	45.6	67.2	67.5		147.37	148.03	
		28	54.6	74.7	69.1		136.81	126.56	
	20	3	45.6	61.8	65.1	63.8 (28 days)	135.53	142.76	116.85
		28	54.6	70.5	66.2		129.12	121.25	

in shear at the joint intervention would easily occur if the void filling were insufficiently operated in the construction stage. Regarding punching shear strength outcomes, the specimens with $W = 15$ mm generally developed the highest punching shear strength in the most test groups. Additionally, the enhanced performances were acquired by comparing the pure compressive strength of laying course. On average, the punching shear strength was increased by up to 134.3% (fully restrained), 127.9% (semirestrained), and 107.2% (nonrestrained). By using these test results as baseline data, it would be necessary to define the long-term performance of rigid SEP in order to design paved loads for heavy traffic volume.

Data Availability

The test results data that support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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