

STUDY ON IMPROVING THE PROPERTIES OF STEEL SLAG TO APPLY FOR PAVEMENT FOUNDATIONS

NGHIÊN CỨU CẢI THIỆN TÍNH CHẤT CỦA XỈ THÉP ĐỂ LÀM LỚP MÓNG TRONG KẾT CẤU ÁO ĐƯỜNG

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Abstract: Nowadays, in Vietnam as in the world, traditional building materials are increasingly scarce while industrial waste is produced more and more. In this paper, the author uses steel slag, a byproduct of steelmaking processes, for replacing crushed aggregate in base or subbase course. Steel slag-stone dust aggregate (70% steel slag and 30% stone dust) are treated with a cement content of 4%-8%. Compressive strength (R_n), splitting tensile strength ($Rech$), and elastic modulus (E) at 7, 14, 28, and 56 days age are investigated. The compressive specimens and splitting tensile strength were obtained by performing tests on 152.4 mm x 116.4 mm (diameter x height). The elastic modulus was as follows 101.6mm x 116.4 mm (diameter x height). The results show that cement-treated steel slag-stone dust aggregate achieved higher compressive strength, splitting tensile strength, and modulus than the cement-treated steel slag aggregate and cement-treated steel slag-fine sand aggregate. In addition, this research proves that cement-treated steel slag-stone dust aggregate with a cement content of 4%-8% can use for base course layers.

Keywords: Cement treated, compressive strength, splitting tensile strength, elastic modulus, subbase, base, steel slag, steel slag-fine sand, steel slag-stone dust.

Classification code: 11.2

Tóm tắt: Hiện nay, vật liệu xây dựng truyền thống ở Việt Nam cũng như trên thế giới ngày càng khan hiếm, thế nhưng các chất thải phát sinh trong sản xuất công nghiệp ngày càng nhiều. Trong nghiên cứu này, nhóm tác giả sử dụng xỉ thép, một sản phẩm phụ của công nghiệp luyện thép, để thay thế cấp phối đá dăm làm lớp móng trên hoặc móng dưới. Cấp phối xỉ thép - đá mi (70% xỉ thép và 30% đá mi) được gia cố với xi măng có hàm lượng từ 4% đến 8%. Cường độ chịu nén (R_n), cường độ chịu kéo khi ép chế ($Rech$) và mô đun đàn hồi (E) của cấp phối trên được khảo sát ở các tuổi 7, 14, 28 và 56 ngày. Mẫu thí nghiệm cường độ chịu nén và cường độ chịu kéo khi ép chế có dạng hình trụ với kích thước 152.4 mm x 116.4 mm; mẫu thí nghiệm mô đun đàn hồi có dạng hình trụ với kích thước 101,6 mm x 116,4 mm. Kết quả thí nghiệm cho thấy, các tính chất trên của cấp phối xỉ thép - đá mi gia cố xi măng như cường độ chịu nén, cường độ chịu kéo khi ép chế và mô đun đàn hồi được cải thiện đáng kể, cao hơn so với cấp phối xỉ thép - cát mịn gia cố xi măng và cấp phối xỉ thép gia cố xi măng. Bên cạnh đó, nghiên cứu này cũng cho thấy cấp phối xỉ thép - đá mi gia cố xi măng với hàm lượng 4% - 8%, có thể sử dụng làm lớp móng trên.

Từ khóa: Gia cố xi măng, cường độ chịu nén, cường độ ép chế, mô đun đàn hồi, lớp móng dưới, lớp móng trên, xỉ thép, xỉ thép - cát mịn, xỉ thép - đá mi.

Mã phân loại: 11.2

1. Introduction

Steel slag, a by-product of steel making, is produced during the separation of the molten steel from impurities in steel-making furnaces. It can apply in various fields such as construction road, concrete aggregate, agriculture [1]. The researches on using steel slag in Vietnam [2] - [6] and overseas [7] - [12] have proved its applicability in construction. A previous study on using recycle steel slag for pavement sub-base road

[13] shows that its characteristics are similar to crushed aggregate subbase course. When the cement-treated steel slag aggregate or cement-treated steel slag-fine sand aggregate with the cement content from 4 to 8% by weight of dry steel slag is commonly used [14], [15], the compressive strength and elastic modulus were improved significantly. However, in the case of cement-treated steel slag aggregate, 14-day splitting tensile strengths are less than 0.35MPa due to not

using for the base course according to regulations in [16] and in the case of cement-treated steel slag-fine sand aggregate, it can be used for road base when treated by 6-8% cement. In this paper, the grain size distribution of steel slag is corrected by mixing with fine sand to make steel slag-fine sand aggregate (SSFSA) or stone dust to make steel slag-stone dust aggregate (SSSDA), then they were treated with portland cement content 4%, 6%, 8%. The compressive strength, splitting tensile strength, and elastic modulus are determined at 7, 14, 28, and 56 days for the aim to evaluate their suitability when applying for pavement.

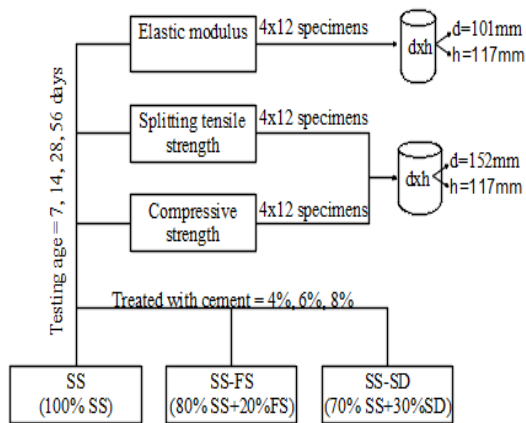


Figure 1. Diagram of testing programming.

Table 1. Physical-mechanical and chemical properties of cement.

Physical properties	Testing standard	Results
Compressive strength at 28 days age (MPa)	TCVN 6016:2011	42,5
Specific gravity (g/cm ³)	TCVN 4030:2003	3,09
Fineness (cm ² /g)	TCVN 4030:2003	3900
Standard consistence (%)	TCVN 6017:2015	32,5
The initial setting time (min)	TCVN 6017:2015	105
The final setting time (min)	TCVN 6017:2015	215

2. Experimental work

2.1 Materials

The materials used for testing include:

2.1.1. Cement:

PCB40 Ha Tien cement is used as a binder in cement-treated materials and its properties were presented in table 1

2.1.2. Water

Water that is used to experiment with is tap water, it satisfies the technical requirements of the TCXDVN 4506-2012 standard.

2.1.3. Steel slag

Steel slag from steelmaker in Ba Ria Vung Tau is collected and recycled by Green Materials company limited. Its physical-mechanical properties are presented in table 2 and table 3.

2.1.4. Fine sand

Fine sand is used for research as natural sand in the Dong Nai river, with physical-mechanical and chemical properties shown in table 4 and table 5 [15].

Table 2. Physical-mechanical properties of steel slag.

Oder	Testing specification	Unit	Mean value	Standard deviation
1	Specific gravity	g/cm ³	3.552	0.0913
2	Bulk dry specific gravity	g/cm ³	3.285	0.0771
3	Bulk Saturated Surface Dry Specific Gravity	g/cm ³	3.361	0.0771
4	Water absorption	%	2.275	0.3561
5	Bulk Density	Kg/m ³	1858.3	56.4
6	Voids	%	48.28	2.42
7	Content of dust, mud, and clay	%	0.953	0.443
8	Los Angeles abrasion and impact	%	21.36	0.971
9	Elongation and flakiness index	%	1.00	0.45
10	Maximum bulk dry specific gravity (proctor compaction test)	g/cm ³	2.458	0.038
11	Optimum moisture	%	3.474	0.204
12	Expansion characteristics	%	0	-
13	CBR in place (K = 0.98)	%	96.96	10.824
14	Module	MPa	248.2	30.24

Table 3. Particle size distribution of steel slag aggregate.

Size sieve (mm)	Pass (%)
50	100,0
37,5	97,3
25	88,9
19	80,7
9,5	52,9
4,75	29,4
2,36	14,4
0,425	3,1
0,075	0,7
<0,075	0,0

Table 4. Particle size distribution of fine sand.

Size sieve (mm)	Pass (%)
4,75	100,00
2,36	99,00
0,425	61,24
0,075	4,91
<0,075	0,00

Table 5. Physical-mechanical and chemical properties of fine sand.

Oder	Testing specification	Unit	Standard	Result
1	Specific gravity	g/cm ³	TCVN 7572-4:2006	2.67
2	Bulk specific gravity	g/cm ³	TCVN 7572-4:2006	2.5
3	Voids	%		46.20
4	Bulk Density	g/cm ³	TCVN 7572-6:2006	1345
5	Water absorption	%	TCVN 7572-4:2006	2.58
6	Organic impurities	Standard reference color	TCVN 7572-9:2006	Equal standard colour
7	Content of dust, mud, and clay	%	TCVN 7572-8 2006	2.08
8	Silica content	mol/l	TCVN 7572-19:2006	62.86
9	Chloride content Cl-	%	TCVN 7572-12:2006	0.007
10	Sulfate and sulfite content	%	TCVN 7572-16:2006	0.012
11	Mica content	%	TCVN 7572-20:2006	0.01

2.1.5. Stone dust

Stone dust is a byproduct of running stones through a crushing machine to make crushed stones: 1 × 1 stone, 1 × 2 stone, or 4 × 6 stone. Nowadays, there is not a standard for instruction on using stone dust, so it was applied in many constructions in the South of Vietnam. Stone dust particles range in diameter from 0 mm to 5 mm and the grain size distribution of steel-slag aggregate shows that it is missed these particles (see table 6 and table 7).

2.2. Choice of mixing ratio for improving aggregate steel slag

Because of recycling techniques and characteristics of steel slag from steelmaker in Ba Ria-Vung tau province, steel slag aggregate lacks small particle sizes (<0,425mm), so that it is difficult to reach compact density and cement-treated SS can not use to base of pavement road [14]. To improve its particle, fine sand, or stone dust, the small size materials, are mixed with steel slag in an optimal proportion. It means that the mixing proportions are the closest to the Fuller curve which will be chosen for studying on the next

step [17, 18]. The grading curves of steel slag-fine sand and steel slag-stone dust in vary ratios (10%-90%, 20%-80%, 30%-70%, 40%-60%, 50%-50%) are compared with the Fuller curve and the results show that the optimal mixing proportion between steel slag and fine sand is 80% and 20% (see figure 2) and the optimal mixing proportion between steel slag and stone dust is 70% and 30% (see figure 3).

2.3. Design of experiments.

A Diagram of testing programming was displayed in figure 1. It was noticed that there were three series of cement-treated aggregates which were designed by adding (4%, 6%, 8%) cement. Each combination includes 36 specimens (see figure 4), whereas 24 specimens are made by modifying proctor mold (height: 11,7cm; diameter 15,2cm) for determination compressive strength according to TCVN 8858:2011 [16] (see figure 5) and splitting tensile strength according to TCVN 8862:2011 [19] (see figure 6) and 12 specimens are made by standard proctor mold (height: 11,7cm; diameter 10.16cm) for determination elastic modulus according to TCVN 9843:2013 [20] (see figure 7).

Table 6. Particle size distribution of stone dust.

Size sieve (mm)	Pass (%)
9,50	100,00
4,75	95,43
2,36	72,39
0,425	25,05
0,075	5,38
<0,075	0,00

Table 7. Physical-mechanical and chemical properties of stone dust.

Oder	Testing specification	Unit	Standard	Result
1	Specific gravity	g/cm ³	TCVN 7572-4:2006	2.782
2	Bulk specific gravity	g/cm ³	TCVN 7572-4:2006	2.624
3	Voids	%		41.01
4	Bulk Density	g/cm ³	TCVN 7572-6:2006	1.548
5	Water absorption	%	TCVN 7572-4:2006	0.56
6	Organic impurities	Standard reference color	TCVN 7572-9:2006	Equal standard color
7	Content of dust, mud, and clay	%	TCVN 7572-8:2006	0.74
8	Dry Compressive Strength	MPa	TCVN 7572-10:2006	209.1
9	Saturated compressive Strength	MPa	TCVN 7572-10:2006	193.6
10	Los Angeles abrasion and impact	%	TCVN 7572-12:2006	14.1

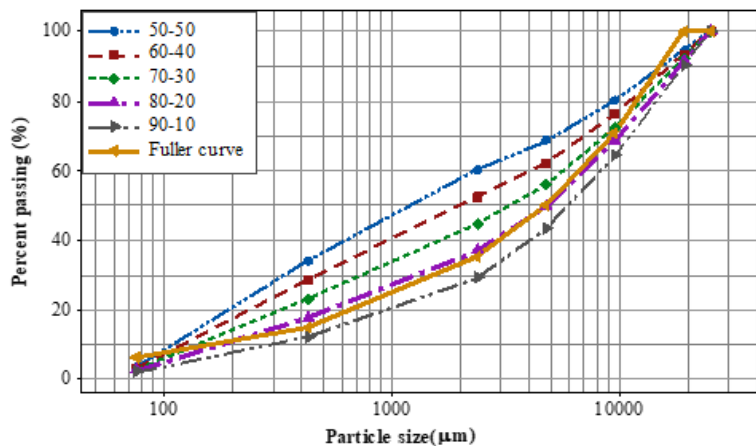


Figure 2. Comparison of grading curves of steel slag -fine sand aggregate with different ratio with fuller curve [15].

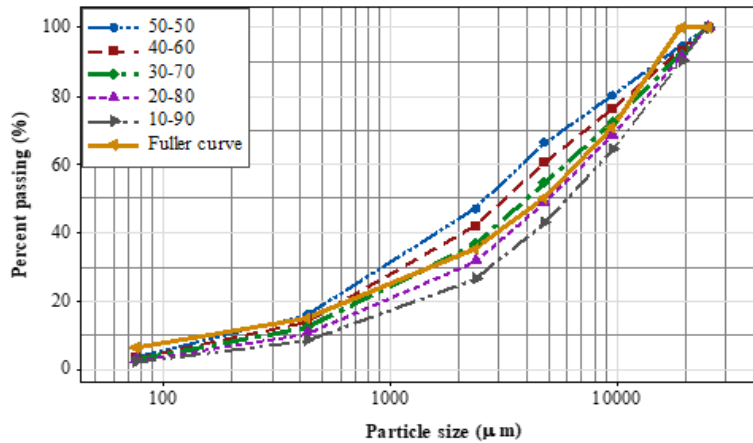


Figure 3. Comparison of grading curves of steel slag-stone dust aggregate with different ratio with a fuller curve.



Figure 4. Testing specimens.



Figure 5. Compressive strength test.



Figure 6. Splitting tensile strength.



Figure 7. Elastic modulus test.

3. Analysis experiment results

The experimental results of cement-treated SSA and cement-treated SSFSA were prepared by the authors yourself from publication [14, 15], were presented in table 8 and table 9, while the experiment results of cement-treated SSSDA are shown in table 10.

Table 8, table 9, and table 10 supply the parameters of cement-treated mixture aggregate with 4%, 6%, 8% percent cement including compressive strength (R_n), splitting tensile strength (R_{ech}), elastic modulus (E_{vl}) that were detected by days 7, 14, 28 and 56.

Table 8. Testing results of cement-treated steel slag aggregate [14]

Cement content	Age days	Mean of compressive strength R_n (MPa)	Mean of splitting tensile strength R_{ech} (MPa)	Mean of elastic modulus E_{vl} (MPa)
4%	7	4.50	0.063	478.25
	14	4.70	0.075	487.35
	28	6.00	0.090	709.26
	56	6.20	0.098	737.43
6%	7	4.90	0.069	581.18
	14	5.20	0.092	592.12
	28	7.00	0.138	902.25
	56	7.40	0.153	940.46
8%	7	5.10	0.084	792.44
	14	5.50	0.124	851.41
	28	11.20	0.396	1319.46
	56	12.10	0.459	1418.17

Table 9. Testing results of cement-treated steel slag-fine sand aggregate [15].

Cement content	Age days	Mean of compressive strength R_n (MPa)	Mean of splitting tensile strength R_{ech} (MPa)	Mean of elastic modulus E_{vl} (MPa)
4%	7	3.80	0.08	1218.46
	14	4.50	0.17	1234.12
	28	6.20	0.30	1306.31
	56	6.60	0.33	1324.28
6%	7	8.50	0.60	1533.35
	14	9.81	0.71	1556.40
	28	11.78	0.88	1710.33
	56	12.06	0.89	1750.14
8%	7	10.80	0.99	1597.13
	14	12.27	1.17	1629.13
	28	15.32	1.39	1862.16
	56	16.80	1.67	1936.41

Table 10. Testing results of cement-treated steel slag- stone dust aggregate

Cement content	Age days	Mean of compressive strength R_n (MPa)	Mean of splitting tensile strength R_{ech} (MPa)	Mean of elastic modulus E_{vl} (MPa)
4%	7	9.06	0.53	1394.18
	14	9.50	0.61	1421.46
	28	11.60	0.74	1468.15
	56	11.80	0.81	1501.32
6%	7	12.10	0.85	1688.18
	14	13.50	0.96	1701.46
	28	16.87	1.14	1794.30
	56	17.61	1.41	1811.45
8%	7	17.40	1.93	1921.41
	14	19.30	2.05	1946.37
	28	24.70	2.56	2050.45
	56	25.90	3.34	2068.25

3.1. Analysis compressive strength R_n

Figure 8 displays the main effects and interaction plots for compressive strength. The effect of varying the operational variables of aggregate, cement content, testing age on the mean compressive strength of cement-treated aggregates is shown. More importantly, it can be seen from the analysis of compressive trends in Figure 8a that among the operational variables investigated, aggregate has the most significant main effect on the response of compressive strength. That is, the connecting line of the mean of compressive strength on the graph for the experimental difference of aggregate has a steeper slope than the others and the ascending order according to aggregates of R_n : SSA \rightarrow SSFSA \rightarrow SSSDA; Cement content also affects on R_n but to a lesser extent, it is observed that by increasing cement ratio, R_n increase too, the rate of gain of R_n is steady when content rises from 4% to 8% displayed by the slope of the connecting line in Figure 8a; Testing age is the least influence on the

development of R_n , during the first stage from 7 to 14 days age, the compressive strength develops slowly, from 14 to 28 days age, the rate of gain of strength is faster shown by the slope of the line in the plot of strength versus age, from 28 to 56 days age, R_n gain slowly. The plot of effect on the age of compressive strength is not linear, it is quadratic relations.

The interaction plot in Figure 8b shows the mean of the compressive strength versus aggregates type, cement content, and testing age. This plot shows apparent interaction effects because the lines are not all parallel, which implies that the relationship between compressive strength and each factor depends on another factor. The analyzed results indicate that the interaction effects for Aggregate*Cement, Aggregate*Age, and Cement*Age are statistically significant.

- The relationship between splitting tensile strength and aggregate type of mixtures depends on the testing age. When using SS, the splitting tensile strength is nearly equal for all cement content. However,

replacing by SS-FS or SS-SD, cement content is associated with substantially different splitting tensile strength, SS-SD and cement content 8% are associated with the highest splitting tensile strength;

- The plot for the Aggregate*Age interaction shows that the effect of testing age on splitting tensile strength is greater for SS-SD than for SS-FS and SS;

- As the same, Cement*Age interaction shows that 8% and 56 - day testing age has higher splitting tensile strength than the others.

Figure 9 is the general plot of compressive strength R_n of three aggregate series in cement-treated versus testing age for different cement content. It can be obverse that the rise of cement content increases the strength of the mixture because cement hydration fills in the pores of the matrix due to forming a large number of rigid bonds in the mixture aggregate. The improved strength by

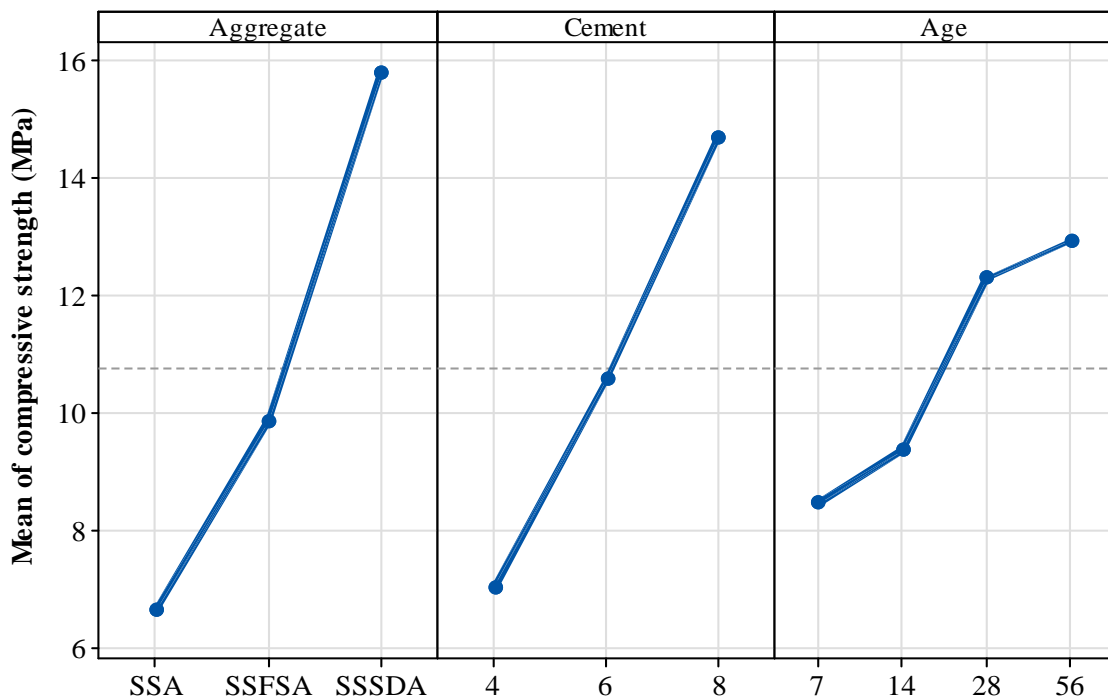
raising the day of testing was also detected in figure 9 which indicates compressive strength obtained at 7 and 14 days age higher than 4MPa for the whole except cement-treated SSFSA with 4% cement content at 7 days age (SSFSA^{4Ce-7D}), its compressive strength is 3.80MPa.

It can imply that cement-treated SSA, SSFSA, SSSDA have 14-day compressive strength suitable for both sub-base and base course when compared to the requirements of compressive strength according to the Vietnam standard [16], [21] were presented in table 11.

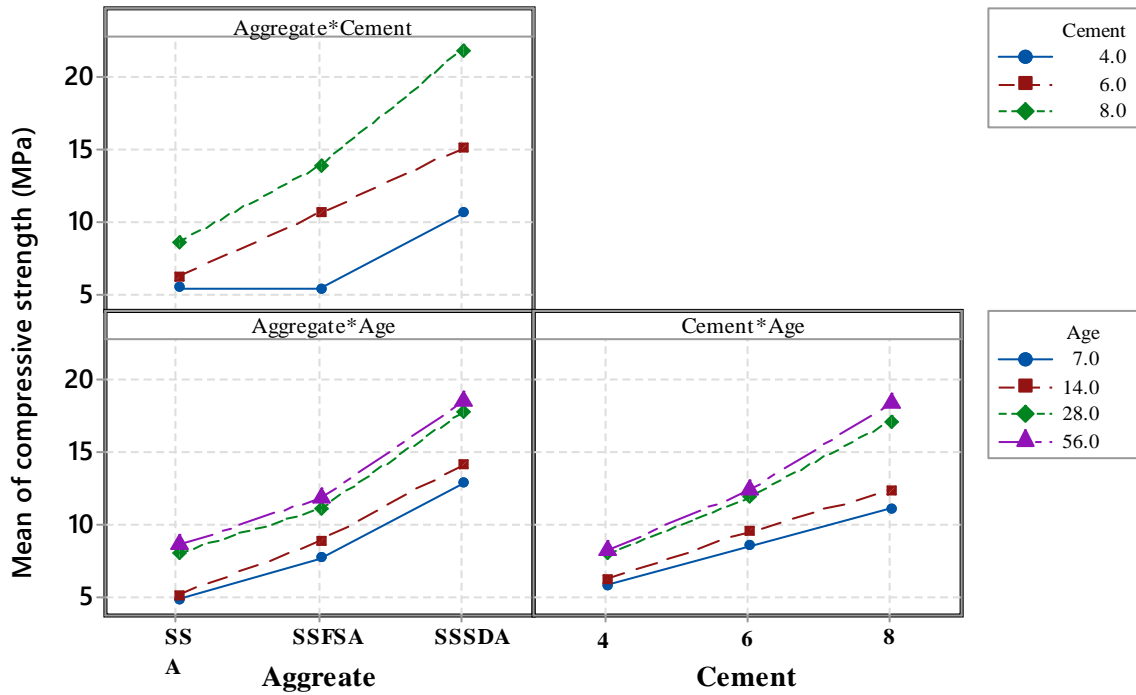
Besides, some different countries use 7-day compressive strength to evaluate the strength of cement-treated base that were listed in table 12. And we can be seen that almost results in figure 9 obtain the strength requirements for the base and sub-base of these countries apart from SSFSA^{4Ce-7D}.

Table 11. Strength requirements for cement-treated base of Vietnam [16], [21].

Name	14-day compressive strength	14-day splitting tensile strength	14-day elastic modulus
Base course	4MPa	0.35-0.45 MPa	600-800 MPa
Sub-Base Course	1.5MPa	Not required	400-600 MPa



(a) Main effects



(b) Interactive effects.

Figure 8. A plot of main effect elements on compressive strength.

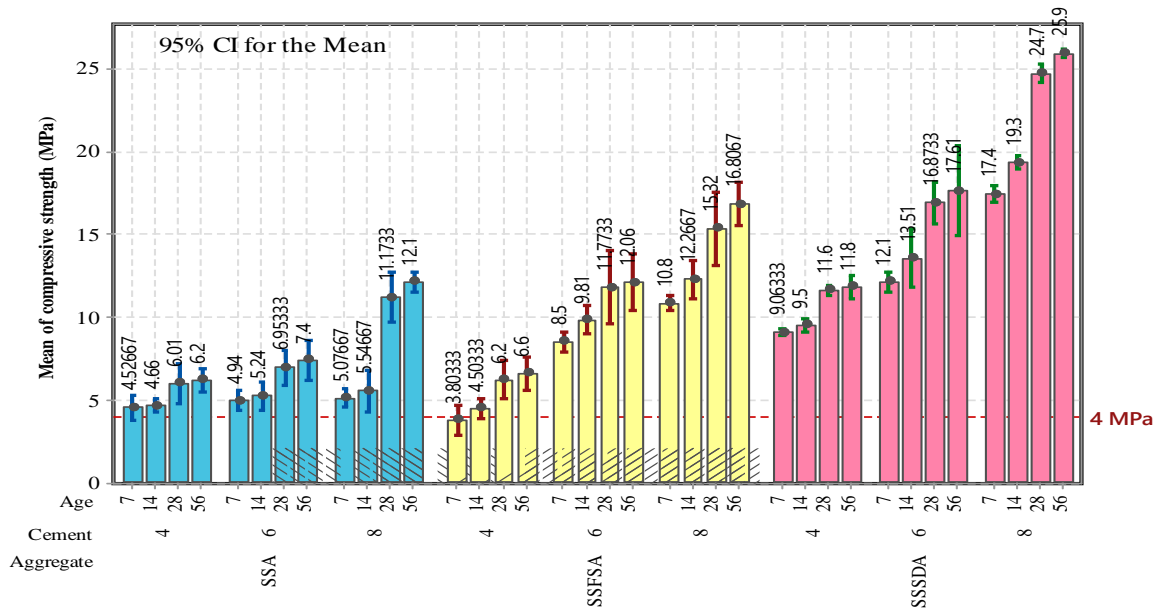


Figure 9. The general plot of compressive strength.

Table 12. Compressive strength requirements for a cement-treated base overseas.

Name	7-day compressive strength	
	Base course	Sub-base course
Texas Transportation Institute [22]	300-750 Psi (2.068-5.171MPa)	250 Psi (1.724MPa)
Iowa [23]	300-800 Psi (2.068-5.516MPa)	
Base course (United Kingdom) [24]	362-652 Psi (4.5-4.75 MPa)	435-652 Psi (2.5-4.5 MPa)
Base course (China) [24]	>290 Psi (>4MPa)	>580 Psi (>2MPa)

3.2. Analysis splitting tensile strength

R_{ech}

Same as analyzed above, Figure 10 shows that three elements (aggregate, cement content, testing age) affect splitting tensile strength with different levels, the influence of aggregate and cement content is more clearly than testing age in which the most important main effect is aggregate (see Figure 10a). The plot in Figure 10b shows that the interaction effects for Aggregate*Cement, Aggregate*Age, and Cement*Age are statistically significant. And the most significant effect was observed on using SSSDA with a high cement content of 8% and the least significant effect was observed on using SS at 56 days age. It is demonstrated that testing age is less effective than cement content on the relationship between splitting tensile strength and aggregate. The general plot of splitting tensile strength R_{ech} was described in Figure 11. The strength was significantly affected by the difference of aggregate in cement-treated.

- With SSA, cement-treated mixture has splitting tensile strength with lowest value, 14-day strength with cement content 4%, 6% và 8% were 0.75 MPa, 0.092 MPa, 0.124 MPa, respectively [14]. This means SSA can only

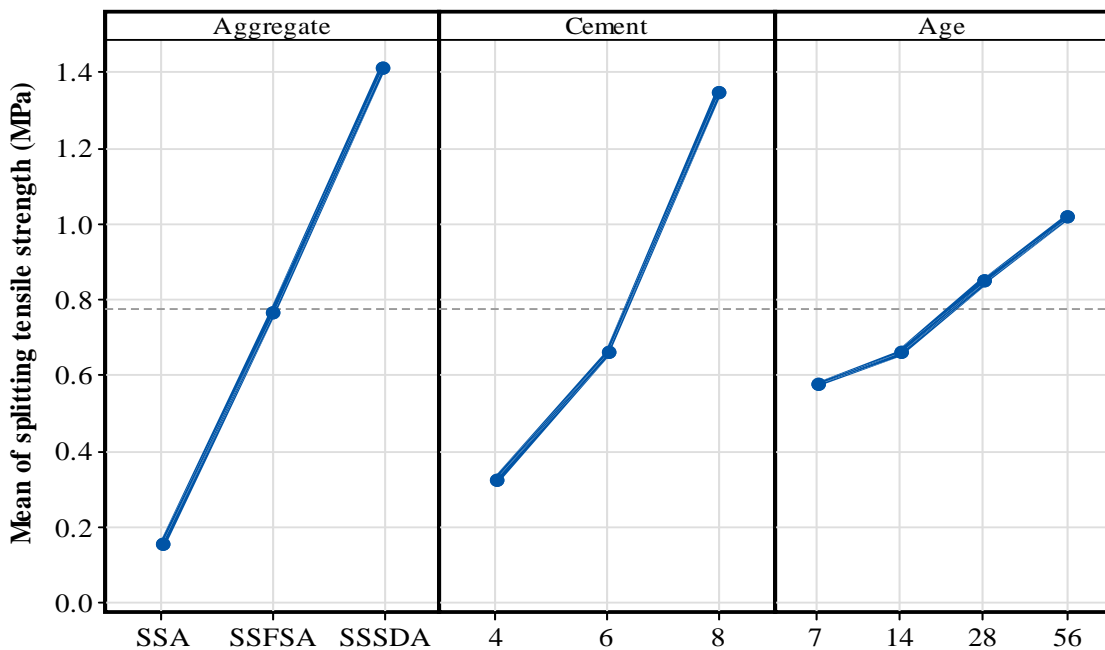
apply for sub-base of pavement because their splitting tensile strengths do not reach the required standard which was listed in Table 11 [16, 21];

- Different from SSA, cement-treated SSFSA with higher splitting tensile strength indicates the combination of steel slag and fine sand has a good effect on splitting tensile strength. 14-day strength with cement content 4%, 6%, and 8% is 0.165MPa, 0.713MPa, 1.169MPa, respectively. And so, SS-SF can be suitable for a base course except for SSFSA with cement content 4% according to Vietnam standard [16], [21];

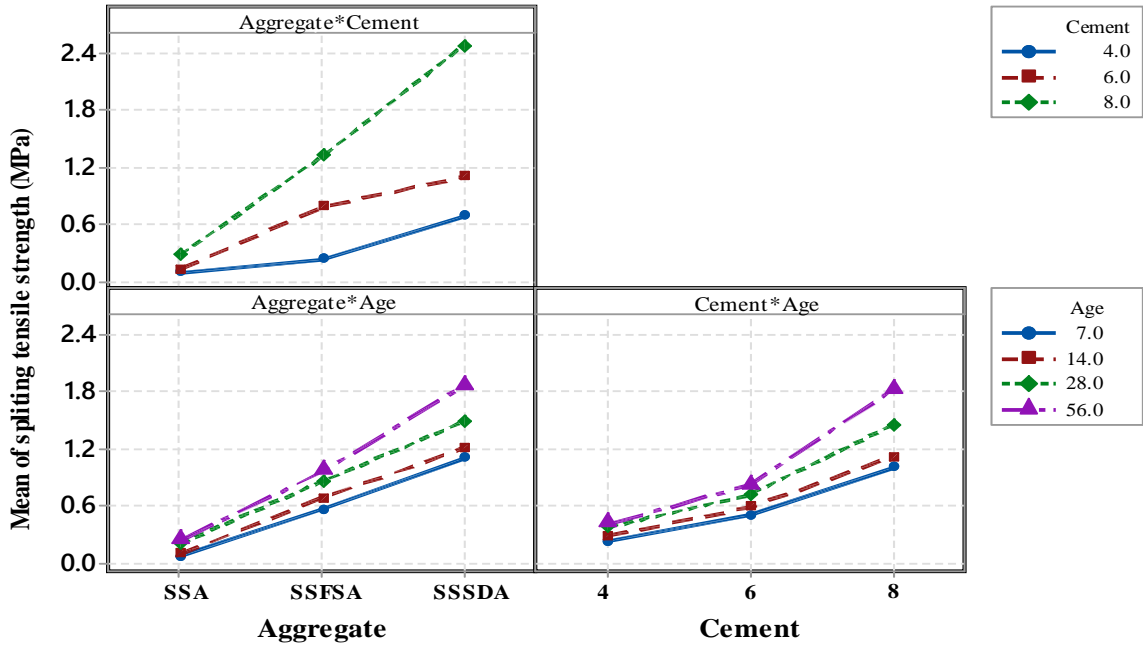
- Cement-treated SSSDA with the highest splitting tensile strength shows a significant effect on steel slag-stone mixing in treated cement. The whole of 14-day strength higher 0.45MPa, the min value is 0.608MPa and the max value is 2.052MPa.

Those values are responding to the criterion not only of Vietnam standard [16], [21] but also China standard [25] for both sub-base and base course.

To summarize, adding fine sand or stone dust supplied the missing particle size for steel slag, consequently, its gradation was also adjusted and the splitting tensile strength was improved significantly.



(a) Main effects



(b) Interactive effects

Figure 10. A plot of main effect elements on splitting tensile strength.

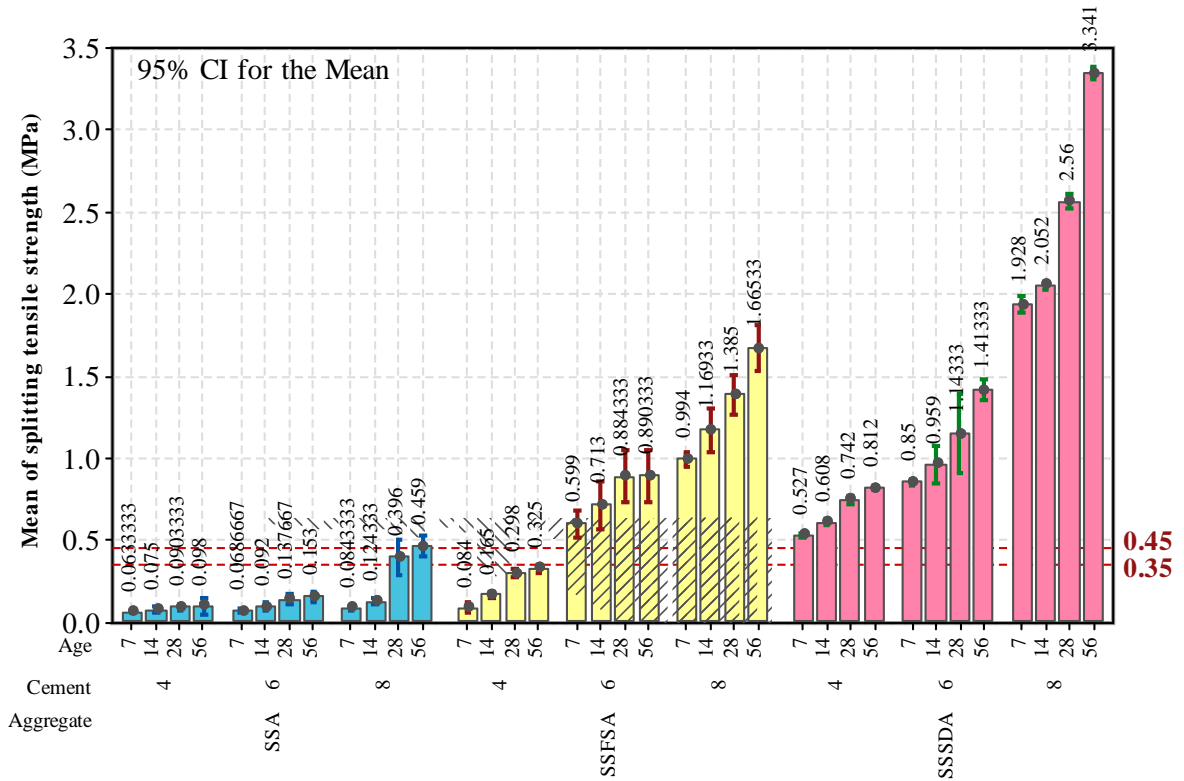
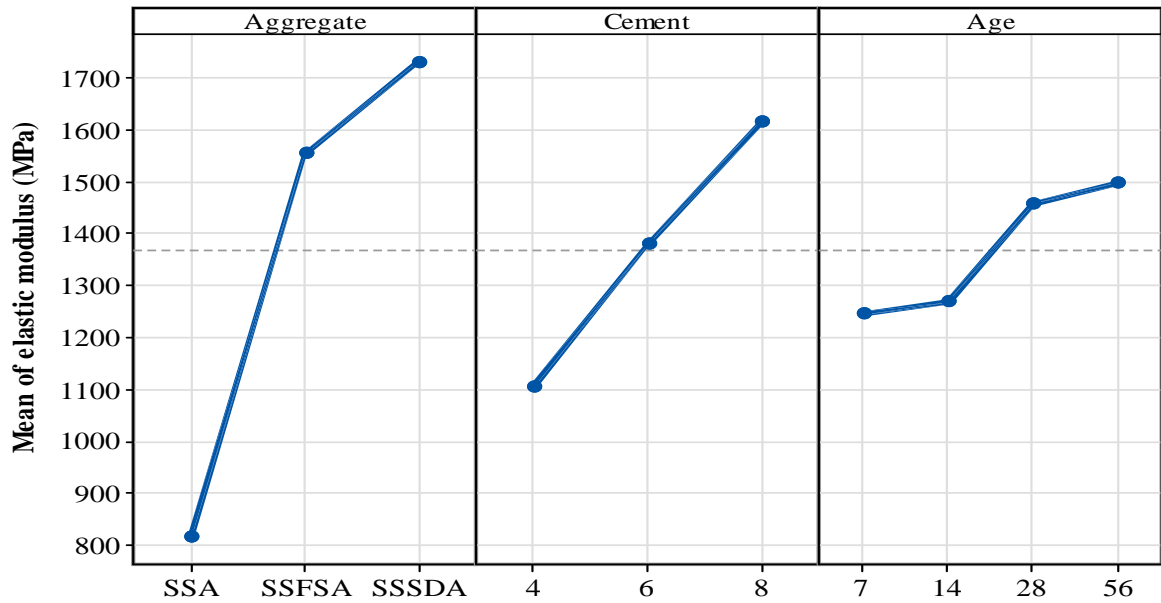
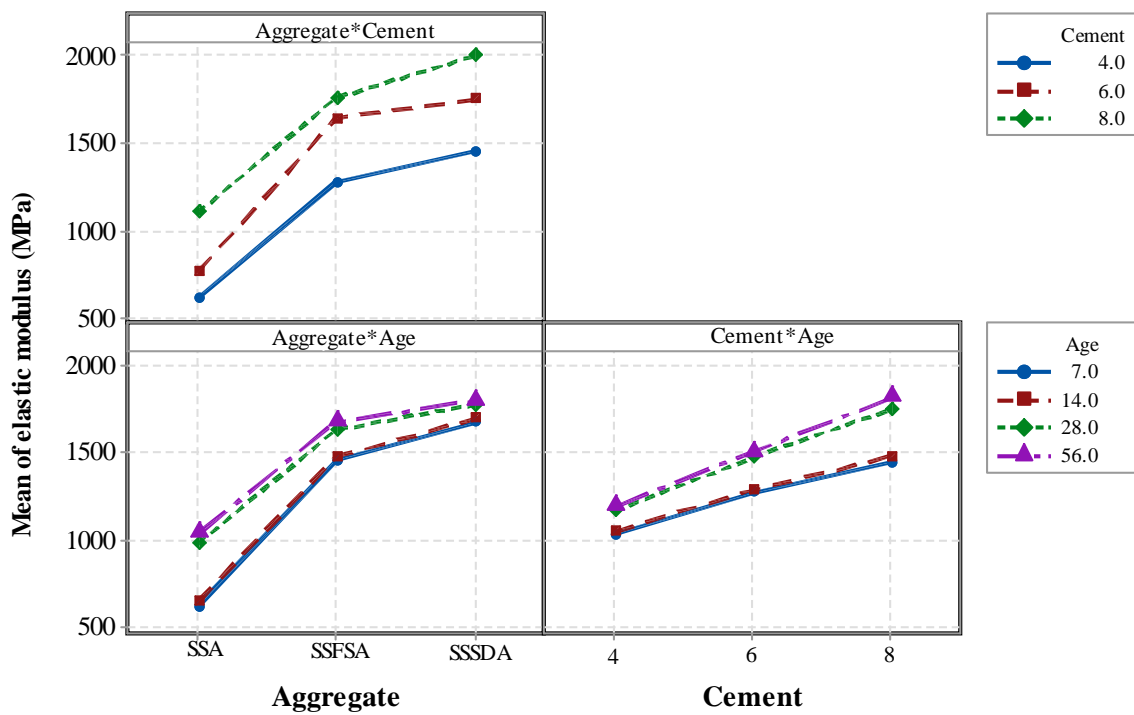


Figure 11. The general plot of splitting tensile strength.



(a) Main effects



(b) Interactive effects

Figure 12. A plot of main effect elements on elastic modulus.

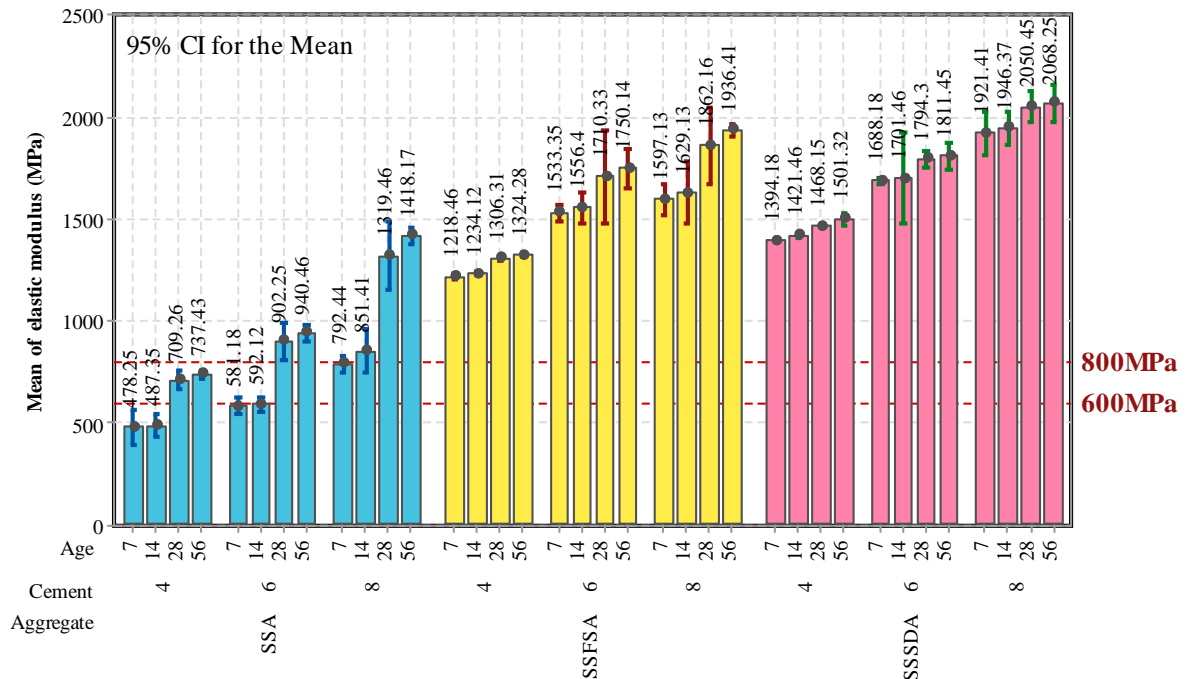


Figure 13. The general plot of elastic modulus.

3.3. Analysis elastic modulus E_{vl}

Like compressive strength and splitting tensile strength, the main effects plot for the elastic modulus was shown in figure 12. It indicates that aggregate is the most influential factor, followed by cement content and finally testing age (figure 12a).

Figure 12b depicts the interaction plot among all the factors. It is clear from the interaction graph that there are some strong interactions between aggregate and cement as well as aggregate and age. However, there is a weak interaction between cement and testing age. The graph in Figure 13 reveals that the elastic modulus of cement-treated SSFSA and SSSDA higher than 800MPa (elastic modulus requirement in Table 11) at any testing age and with any cement content. These values at 7 days age are about 1218-1394MPa nearly by the design values of those road base materials according to the criterion JTJ014-97 (1300-1700MPa) “Specification of Asphalt Pavement Design for Highway” of the Ministry of Communications of China [25]. It means that cement-treated SSFSA and SSSDA reach the claim for the elastic modulus of base course follow both Vietnam and China standards.

4. Conclusion

When steel slag is mixed with fine sand or stone dust with a ratio of 80% -20% and 70% -30%, respectively, to create steel slag-fine sand and steel slag-stone dust aggregate. The compressive strength, splitting tensile strength, and elastic modulus parameters are significantly improved. Based on the analysis experimental results presented above, some conclusions can be given by:

- Aggregate, cement content and testing age are three factors that affect compressive strength, splitting tensile strength, and elastic modulus. However, aggregates are the most significant effect factor;
- The interaction effect between aggregate and cement content is strongest;
- With the same cement content and testing age, the ascending order of compressive strength, splitting tensile strength, and elastic modulus as follow: Cement-treated SSA \rightarrow Cement-treated SSFSA \rightarrow Cement-treated SSSDA;
- Cement-treated SSFSA and cement-treated SSSDA with cement content 4%-8% can use for both sub-base and base course of pavement road excepting cement-treated SSFSA with cement content 4% \square

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