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Original Article

Compound soil-tyre chips modified by cement as a road construction material

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Abstract

This research attempts to overcome the two problems of low-quality soil and a growing number of discarded tyres by mixing low-CBR soil with recycled tyre chips. The compound soil-tyre chips was then stabilised by Portland cement with the aim of using them as a new material in road construction in order to reduce the occurrence of shrinkage cracks. To achieve the purposes of this research three standard geotechnical testing programmes were employed: (1) modified compaction tests, (2) California Bearing Ratio tests (CBR), and (3) unconfined compression tests. The modified compaction test results proved that for the mixtures having very low tyre chips and cement content, the behaviour is very complex. It was also observed that the greater the percentage of rubber added the lower the global density. However, this is predictable as the specific gravity of the rubber is much lower than that of the soil. For the relationship between the optimum moisture content (OMC) and the cement content, it was observed that there is no clear pattern.

For the specimens having no cement added, the CBR for unsoaked specimens was observed to be greater than that for soaked specimens. However, when the cement was introduced the CBR test showed that the resistance to penetration for the soaked specimens was significantly greater, indicating the effects of cement added on the strength. In addition, it was found that the CBR values for both soaked and unsoaked specimens gradually increased with the increase of cement content. Lastly, the unconfined compressive strength progressively increased with the increase of cement.

Keyword: tyre chips, cement stabilisation, CBR, shrinkage crack

1. Introduction

Due to the lack of high quality geometerials for the construction of roads and embankments in Thailand, civil engineers have repeatedly attempted to improve whatever materials are available for the task. Suitable materials may exist; however, quite often their location is so far from a construction site that the cost of transportation may not be feasible for the project. According to Hausmann (1990), soil improvement techniques may be classified as mechanical modification, hydraulic modification, physical and chemical modification, and modification by means of inclusions and confinement.

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It has been widely recognised that Portland cement can be used to increase the shear strength and stiffness of soils because it can be mixed with almost every soil type having various textures and sizes. The other benefit of cement stabilisation is that the cement-treated soil has a better stability in terms of volume change as well as a higher durability, which are the properties required for road construction. Furthermore, the construction of cement-stabilised soil does not require advanced techniques and technologies, i.e., simply spreading cement and mixing, applying water and mixing, and finishing with the conventional compaction. Even though a wide range of soil types may be improved by mixing with cement; nonetheless, the greatest effectiveness and economy are achieved when it is mixed with sands, sandy soils, and clayey soils having low to medium plasticity (FHWA., 1979).

However, if not well-designed and poorly-controlled during construction, transverse shrinkage cracking may occur, especially at or near a surface. It should be noted that such cracks are normal for soil-cement construction (PCA, 1995). Normally, this will not affect a road base itself in terms of performance. In the case that the shrinkage cracks are too large such as wider than 3 mm, however, damage to the pavement may occur. Thus, there have been several techniques to minimise the occurrence of the shrinkage cracks. For example, before placing a cement-treated base a bituminous layer is laid first. Then, the soil-cement is constructed a few days later.

Discarded tyres have been widely regarded as solid waste as a result of industrial development. They have become an increasingly global problem because disposing of them in open areas is a danger to the environment. For example, they are vulnerable to fire. If this happens; they may then contaminate groundwater. The consequences would be disastrous as it may take hundreds of years for the groundwater to become clean again. In addition, the available techniques needed for the task could not assure the outcome. As such, disposing of whole used tyres has been prohibited by the new EU Landfill Directive since July 2003 (Khalid and Artamendi, 2004). Thus, making use of them needs to be considered imaginatively and the solutions must be sustainable.

Each year, in the United States over 250 million of waste tyres are stockpiled (RMA, 2004), and more than 28 million of passenger car tyres are discarded in Canada (Garga and O'Shaughnessy, 2000). In the case of Thailand, the accumulated number of registered cars up to the 31st of December 2009 was almost 27 million (Department of Land Transport Web Site). Consequently, if each vehicle needs tyre changing every three years; each year the waste tyres would be approximately 36 million. Moreover, it seems that acquiring a car for Thai people is becoming easier as the average income is gradually increasing. Considering these figures, it is apparent that Thailand needs to think sensibly about how to manage the waste tyres in the near future.

Several investigators have studied the shear strength and deformation characteristics of sand mixed with recycled tyre chips. Numerous results indicate that the shear strength of the mixture is increased, depending on tyre chip content as well as on the aspect ratio of the tyre chips. For soils having a low CBR (California Bearing Ratio) value, however, mixing them with the tyre chips may not improve its overall shear strength and stiffness. Thus, this research aimed at improving those low-CBR soils mixed with tyre chips by introducing Portland cement so that the mixture could be used as a road construction material such as sub-base or even base layer.

2. Research Objectives

The main objective of this research was to investigate the possibility of mixing soil having a low-CBR value with

recycled tyre chips. The soil-tyre chips mixtures were then stabilised by introducing Portland cement having various cement contents, resulting in a soil-tyre chips-cement matrix that is suitable for a road base or road sub-base layer. To minimise the variables of the research, only one soil type and one size of tyre chips were investigated. Hence, the only variable remaining was the percentage of Portland cement to be mixed with the compound soil-tyre chips.

The modified compaction test was employed to determine the maximum dry density as well as optimum moisture content (OMC). Then, the OMC values were used to prepare specimens for the California Bearing Ratio (CBR) test, both soaked and unsoaked. Note that the CBR values are the main property that is required for the design of road embankments. In addition, the unconfined compression test was also conducted to obtain the undrained shear strength, which is the most common type of shear strength used for the evaluation of soil-cement stabilisation.

3. Materials, Test Programmes, and Methods

This research aimed to improve low-quality soil for the purpose of using it as a road sub-base or base layer because good-quality geomaterials are increasingly difficult to obtain with reasonable cost. To achieve this, cement and tyre chips were employed to be mixed with such soil. It should be noted that cement has been widely used to increase the strength of soil. For tyre chips, however, they are becoming an environmental problem and need to be carefully managed. As such, making use of them for road construction would be a sustainable solution as a vast quantity is required.

The first task of this research was to find a lateritic soil that is abundant in the South of Thailand but not good enough for road construction. The base material, a lateritic soil, was obtained from Satul, a province in the South of Thailand, 973 km from Bangkok. The soil was chosen because its CBR is quite low, i.e., just 18%. It had a specific gravity G_s of 2.64, which is relatively low compared to other similar soils in Thailand such as 2.68, as studied by Saowapakpiboon *et al.* (2010). The true scale picture of the soil is shown in Figure 1(a). The mean particle size of the soil D_{50} was 1.6 mm, the coefficient of uniformity $C_u = 5.4$, and the coefficient of curvature $C_g = 0.5$. The size distribution curve for the soil is illustrated in Figure 2(a). In addition, according to the Unified Soil Classification system, the soil has been classified as SP



Figure 1. True-scale pictures for (a) test soil and (b) tyre chips



Figure 2. Particle size distribution curves for (a) soil and tyre chips (b) compound soil-tyre chips (c) soil, tyre chips, and compound soil-tyre chips

(Poorly-Graded Sand).

Recycled tyre chips were obtained commercially from KKI Recycle, Nakhonpathom, Thailand. The specific gravity of the tyre chips was 1.11, which is quite similar to those studied by Promputthangkoon and Hyde (2010). The true scale picture of the tyre chips is also shown in Figure 1(b). Note that a common range of G_s for the recycled tyres reported by Edil and Bosscher (1994) is 1.13 to 1.36. The D_{50} of the rubber was about the same as that of the soil. The size distribution curve for the tyre chips is illustrated in Figure 2(a).

The mixtures were prepared by mixing the soil with the rubber according to weight. This is because it would be easier for controlling the soil and rubber proportions. However, in the field mixing by means of volume would be more convenient. Converting the mixtures prepared by weight to be mixtures by volume can be done by using the specific gravity values for the soil and the tyre chips already reported.

The soil to rubber ratios were 100:0, 98:2, 93:7, 85:15, and 75:25; they were named as 100S, 98S, 93S, 85S, and 75S, respectively. These mixtures were weighed accordingly and particle size analysis performed using a simple sieving technique. The size distribution curves for all mixtures including the soil and tyre chips are also illustrated in Figure 2(c). Next, each mixture was mixed with Portland cement ranging from 0, 1, 5, 10, and 15%. Note that the cement portion was calculated based on the soil portion. This resulted in a total of 25 mixtures. To achieve the objectives of this research project three standard test programmes were conducted: (1) modified compaction tests, (2) California Bearing Ratio tests (CBR), and (3) unconfined compression tests.

As the rubber in soil-tyre chip matrices is highly compressible, the modified compaction test was chosen over the stand compaction test because it provides a higher energy that is needed to compact the compound soil-rubber. The procedures for the modified compaction test were in accordance with ASTM D 1557-02 (2003). For the CBR test the standard test methods provided by ASTM D 1883-99 (1999) were employed. For the mixtures containing high amounts of cement, a universal testing machine (UTM) was utilised to penetrate the specimens because the capacity of the standard CBR machine was not enough (see Figure 3). The unconfined compressive strength was determined by the procedures detailed in ASTM D 1633-00 (2000). The details of all of the mixtures, test numbers, and test methods are shown in Table 1.



Figure 3. (a) Conventional CBR machine (b) CBR test by UTM

%Soil	%Rubber	%Cement*	Compaction	CBR	UCS
100	0	0	CP100S0	CB100S0	UC100S0
		1	CP100S1	CB100S1	UC100S1
		5	CP100S5	CB100S5	UC100S5
		10	CP100S10	CB100S10	UC100S10
		15	CP100S15	CB100S15	UC100S15
98	2	0	CP98S0	CB98S0	UC98S0
		1	CP98S1	CB98S1	UC98S1
		5	CP98S5	CB98S5	UC98S5
		10	CP98S10	CB98S10	UC98S10
		15	CP98S15	CB98S15	UC98S15
93	7	0	CP93S0	CB93S0	UC93S0
		1	CP93S1	CB93S1	UC93S1
		5	CP93S5	CB93S5	UC93S5
		10	CP93S10	CB93S10	UC93S10
		15	CP93S15	CB93S15	UC93S15
85	15	0	CP85S0	CB85S0	UC85S0
		1	CP85S1	CB85S1	UC85S1
		5	CP85S5	CB85S5	UC85S5
		10	CP85S10	CB85S10	UC85S10
		15	CP85S15	CB85S15	UC85S15
75	25	0	CP75S0	CB75S0	UC75S0
		1	CP75S1	CB75S1	UC75S1
		5	CP75S5	CB75S5	UC75S5
		10	CP75S10	CB75S10	UC75S10
		15	CP75S15	CB75S15	UC75S15

Table 1. Summary of mixtures, test programmes, and test numbers.

* The cement was calculated based on the soil portion

4. Results and Discussion

The test results are summarised in Table 2. It displays sample number, mixtures and corresponding cement content (CC) added, optimum moisture content (OMC), maximum dry density, soaked and unsoaked CBRs, and unconfined compressive strength. Details of the results for each test as well as its graphical results are shown and discussed in the respective sections below.

4.1 Modified compaction tests

The maximum dry density $\rho_{d,max}$ and its corresponding optimum moisture content OMC for each sand-rubber mixture were plotted against the cement content, as illustrated in Figure 4(a). In addition, the relationship between the OMC and the cement content was plotted and illustrated in Figure 4(b).



Figure 4. (a) Maximum dry density vs. cement content (b) OMC vs. cement content

Commla		%Rubber	%Cement*	Compaction		CBR (%)		LICS
No.	%Soil			OMC (%)	Max. Dry Density (g/cm ³)	Unsoaked	Soaked	$q_{\rm u}$ (kPa)
100S	100	0	0	12.7	1.832	19	18	227
			1	15.3	1.796	23	25	291
			5	12.5	1.871	145	181	1063
			10	13.1	1.844	488	566	1481
			15	10.7	1.890	624	691	1804
98S	98	2	0	12.0	1.819	10	6	195
			1	12.7	1.780	26	14	223
			5	10.2	1.868	98	111	715
			10	11.8	1.812	297	330	978
			15	11.5	1.829	468	570	1213
93S	93	7	0	14.5	1.624	4	2	37
			1	12.1	1.678	10	5	87
			5	14.9	1.688	52	60	416
			10	13.6	1.731	101	121	712
			15	11.9	1.786	298	336	750
85S	85	15	0	13.4	1.580	3	1	15
			1	13.2	1.591	5	4	53
			5	13.4	1.588	24	44	287
			10	12.8	1.600	59	66	511
			15	12.6	1.592	121	132	532
75S	75	25	0	14.1	1.410	1.3	0.6	8.2
			1	14.0	1.412	2	2	29
			5	13.1	1.418	11	8	181
			10	13.5	1.454	22	23	211
			15	13.1	1.453	39	42	287

Table 2. Summary of test results.

* Based on the soil portion

Overall, it was found that the $\rho_{d,max}$ is gradually decreased with the gradual increase of the tyre chips content (*TC*). This, however, was predictable as the G_s for the rubber is significantly smaller than that of the soil. As a result, when the soil was mixed with the rubber, the global unit weight of the mixture was subsequently lower than that of pure soil. When considering Figure 4(a), the compaction characteristics may be divided into three groups: group (1) 100S and 98S, group (2) 93S, and group (3) 85S and 75S.

For group (1) the initial $\rho_{d,max}$ (no cement added) was about 1.83-1.84 g/cm³. When 1% of CC was added, however, the $\rho_{d,max}$ surprisingly decreased to around 1.78-1.79 g/cm³. Then it increased again after 5% of CC was added; and, this time it was slightly greater than that of the specimens whose mixtures has no CC. However, when the CC was increased to 10% the $\rho_{d,max}$ was lower than that of the mixtures having 5% CC; and, it increased after the CC was increased to 15%. This complex behaviour may be due to the fact that this is a five-phase composite material, comprising air, water, soil, rubber, and cement. For example, during the mixing and especially the compaction test the void ratio may be altered due to the disturbance as well as the force applied. The alteration of the void ratio then may cause the changes in pore and pore water pressure. In addition, this may also influence the effectiveness of the compaction due to either the increase or the decrease of the pore and pore water pressure. The effects of mixing materials having different particle sizes on minimum and maximum void ratios have been reported and discussed by Lade *et al.* (1998).

For group (3), it seems that the addition of CC had no effects on the compaction characteristics as the $\rho_{d,max}$ for all of the mixtures was very similar, regardless of how much CC was added. For group (2) the initial $\rho_{d,max}$ was much lower than that of 100S. However, it progressively increased with the increase of the CC. This distinguishing behaviour of group (2) suggests that it may represent a transitional condi-



Figure 5. Soaked and unsoaked CBRs for (a) 100S (b) 98S (c) 93S (d) 85S (e) 75S

tion between group (1) and group (3). In other words, the transitional condition is where the mixture containing the rubber content between 2% and 15% causes the maximum dry density to increase virtually linearly, unlike the other two groups. This, however, needs to be further studied. For the OMC behaviour, it was observed that there is no clear pattern for any of the mixtures. Nonetheless, overall when the CC was greater the OMC required was generally lower, as evident in Figure 4(b).

4.2 California bearing ratio tests

The values of the CBR tests for both unsoaked and soaked specimens of 100S, 98S, 97S, 85S, and 75S were plotted and are shown in Figures 5(a), (b), (c), (d), and (e), respectively. In addition, the values of CBR for all of the unsoaked specimens and for all of the soaked specimens were plotted together and are illustrated in Figures 6(a) and (b), respectively, in order to be able to compare the behaviour when the rubber portion was varied.

For the CBR tests for all mixtures having zero CC, it was found that generally the CBR values for the unsoaked specimen were slightly greater than those of the soaked ones. However, when the cement was introduced the CBR values for the soaked specimens were much greater. These results indicate the effects of the cement on the CBR in terms of the increase of the strength and stiffness. Predictably, it was observed that as the percentage of rubber was gradually increased from 2% to 25%; a gradual decrease of the CBR was observed. This may lie on the fact that the compressibility of the rubber is greater than that of the soil. As a result, resistance to penetration was observed to be lower than that of pure soil, as observed in the CBR test results.

Presumably, the CBR value required for a road base is 100%. For pure soil (100S) specimens, both soaked and unsoaked, without the addition of cement, it can be seen that the CBR is just 18% to 19%; but, it was substantially increased to over 600% when 15% of cement was added. Nonetheless, the unsoaked specimen required only approximately 3% cement to attain the CBR of 100%, as evident in Figure 5(a). Thus, it was interesting to apply this analogy to all of the other mixtures. The summary of the percentage of CC required for the mixtures to attain the 100% CBR is shown in Table 3. Notice that for 75S, the CBR values were very low even when the CC was at a maximum of 15%. Thus, it may be suggested that this particular mixture is not suitable as a road base structure.

From Table 3, the results were further analysed by plotting the relationship between the cement content required for the mixture to attain the CBR of 100% ($CC_{(CBR100)}$ in %) versus the tyre chip contents (TC in %), as illustrated in Figure 7. Subsequently, the following polynomial equation was

Sample No.	%Soil	%Rubber	%Cement Required for 100% CBR
100S	100	0	2.9
98S	98	2	5
93S	93	7	10
85S	85	15	13
75S	75	25	N/A*

Table 3. Cement content required for unsoaked specimensattaining a CBR of 100

* At maximum CC the CBR < 100%

obtained:

$$CC_{(CBR100)} = 2.76 + 1.13(TC) - 0.04(TC)^2$$
 (1)

This equation could be used to predict how much cement content is required for a soil-rubber mixture having a certain amount of rubber to attain the 100% CBR. From these results and discussion, it may be suggested that recycled rubber regarded as solid waste together with Portland cement may be used to mix with poor-quality soil to increase the shear strength and stiffness in order to be used as a road construction material. It should be noted that equation (1) was derived based on a specific soil. However, it could also be employed for other soils having similar gradation and properties.

4.3 Unconfined compression tests

The unconfined compressive strengths (q_u) summarised in Table 2 were plotted and are shown in Figure 8. Overall, it was found that the q_u gradually increased with the increase in cement content. When there was no cement added, the q_u values for 100S and 98S were very similar, indicating that the behaviour of compound soil-rubber was still dominated by the soil; moreover, the rubber was just floating in the soil-rubber matrices.

The characteristics of the q_u versus cement content graphs for all mixtures indicate that the q_u behaviour may be categorised into two groups: group (1) 100S and 98S, and group (2) 93S, 85S, and 75S. The maximum q_u for 100S having 15% of cement was 1804 kPa. This is similar to that of finegrained soil mixed with the same amount of cement as reported by FHWA (1979). It was also observed that when a small amount of cement of just 1% was added, the q_u was quite similar to that of the specimen having no cement, indicating a very small effect of the cement. However, when the cement content was increased to 5% the q_u was dramatically increased. After that, the q_u was progressively increased almost linearly. This behaviour for 100S was also observed for 98S, except that the q_u was quite smaller; i.e., the maximum q_u for 98S was just 1213 kPa.

For group (2), the initial q_u values (no cement added) for 93S, 85S, and 75S were 37, 15, and 8.2 kPa, respectively. Notice that these values are very low compared to those of group (1). When a small amount of cement content of 1% was added, the q_u values were observed to be slightly increased: they were 87, 53, and 29 kPa, for 93S, 85S, and 75S, respectively. They continued to increase almost linearly when the cement was increased from 5% to 10%. However, it can be seen that at a maximum cement content of 15%, the q_u values are very similar to those mixtures having 10% cement content. This indicates that the effectiveness of the cement added as high as 15% is no better when a mixture contains high proportions of rubber. The maximum q_u values for 93S, 85S, and 75S were 750, 532, and 287 kPa, respectively.

5. Conclusions

A lateritic soil that is abundant is the South of Thailand, Satul province, was chosen as a base soil to be mixed with recycled tyre chips and stabilised by Portland cement for the purpose of using them as a road construction material. The soil to tyre chips ratios by weight were 100:0, 98:2, 93:7, 85:15, and 75:25. Each mixture was mixed with Portland cement ranging from 0, 1, 5, 10, and 15%, based on the soil portion.

To achieve the aims of the research three standard geotechnical testing programmes were conducted: (1) modified compaction tests, (2) California Bearing Ratio (CBR) tests, and (3) unconfined compression tests. The purpose of the modified compaction test was to obtain the attainable maximum dry density as well as its corresponding water



Figure 6. CBR values for all mixtures (a) unsoaked samples (b) soaked samples



Figure 7. Cement content at CBR = 100 vs. tyre chips content.



Figure 8. q_{μ} values for all mixtures vs. cement contents.

content, in the other word, Optimum Moisture Content, known as OMC. The OMCs then were used to prepare specimens for the CBR tests, both soaked and unsoaked. The CBR values would give a very important parameter indicating whether a mixture is suitable for road construction. The unconfined compression test was conducted to provide another property that is essential for geomaterial stabilised by cement, which is unconfined compressive strength. Based on the experiences, test results, and analyses, the following conclusions have been drawn.

(1) The specific gravity values for the soil and tyre chips are 2.64 and 1.11, respectively.

(2) The mean particle sizes for the soil and the rubber are very similar; they are about 1.6 mm.

(3) The coefficient of uniformity C_u and the coefficient of curvature C_g for the soil are 5.4 and 0.5, respectively. These result in the soil classified as SP, according to the Unified Soil Classification system.

(4) Overall, the maximum dry density ρ_{dmax} is gradually increased with increased cement content. However, the $\rho_{d,max}$ values for 100S and 98S having 1% of cement are actually lower than those specimens having no cement. This may be due to the fact that the mixture is a five-phase composite material comprising soil, rubber, cement, water, and air, whose behaviour is very complex and needs to be further studied.

(5) It was found that there is no clear pattern for the OMC values against the cement content.

(6) The CBR values for both soaked and unsoaked are gradually increased with the increase of cement content.

(7) For the mixtures having no cement added the CBR for unsoaked specimens is slightly greater than those of soaked specimens. However, this is contrary for the mixtures that were mixed with cement, i.e., the CBR values for soaked specimens are greater.

(8) As predicted, the unconfined compressive strength is gradually greater with the increase of cement content.

(9) Discarded tyres are vulnerable to fire. Thus, disposing of them in open areas is a danger to the environment. For example, the burnt tyres would contaminate the groundwater. It then may take over hundreds of years for the groundwater to become clean again. It is therefore suggested that making use of them as a road construction material by placing them at lower layer could prevent the disaster.

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