Chapter IV

RESULTS AND DISCUSSION

1. Mixing Water Required to Produce Uniform Coating of Asphalt

In order to obtain a uniform mix of soil-emulsion mixture, a minimum suitable amount of water should be added to soil before it is mixed with emulsion. This added water will precoat the soil particles and help to prevent immediate chemical reaction between the negative surface charge of soil particles and the cationic emulsion, and also will tend to delay the mixing time. By trial-and-error method described in Chapter III, the minimum percentages of water required for adding to silty sand and beach sand before being mixed with various percentages of emulsion were determined and summarized in Table 7. The results for soil-lime-emulsion stabilization and soil-cement-emulsion stabilization are also shown in the table. For soil-emulsion mixture, it is found that, with same percentage of emulsion, the required amount of added water for silty sand is equal to that for beach sand. However, these values of mixing water appear to be varied with the percentage of emulsion. The higher the percentage of emulsion, the smaller amount of water is required. Such decrease in mixing water with the increase in emulsion content is considered to be due to the fact that the emulsion itself consists of asphalt and water.

In the case of soil-lime-emulsion stabilization, as mentioned in Chapter III, lime was mixed with dry soil and emulsion was added

Table 7 - Mixing Water Required to Produce Uniform Coating of Asphalt

Soils	Stabilizers			Mixing Water, %*
	Emulsion,%*	Lime,%*	Cement,%*	
Silty Sand	3	-	-	16
"	4	-	-	15
"	5	-	-	14
"	2	3	-	19
"	3	3	-	18
"	4	3	-	17
"	2	-	3	17
"	3	-	3	16
"	4	-	3	15
Beach Sand	3	-	-	16
"	4	-	-	15
"	5	-	-	14
"	2	3	-	10
"	3	3	-	9
"	4	3	-	8
"	2	-	3	17
"	3	-	3	16
"	4	-	3	15

* Based on over-dried weight of soil

later to soil-lime mixture. The results shown in Table 7 for this type of stabilization are the values of the percentage of added water required for moistening the soil-lime mixture before the emulsion is added. With the same percentage of emulsion, the amount of mixing water for silty sand with 3 % lime appears to be slightly larger than that for silty sand without lime. This phenomenon may be explained by the additional amount of fines in the added lime which require more precoated water, as well as by chemical reaction. But as lime is added to beach sand, the reversal occurs. The results obtained show that, when mixed the same percentage of emulsion, the amount at water required for adding to beach sand with 3 % lime is much samller than for adding to beach sand without lime. This indicates that lime added to beach sand has significant effect on the dispersion of emulsion thus a uniform coating of asphalt can be produced with the presence of very small amount of added water.

For soil-cement-emulsion system, as cement is added later to soil-emulsion mixture, the suitable minimum amount of mixing water for this type of stabilization is therefore the same as that for producing a uniform mix between soil and emulsion in soil-emulsion system.

One word of caution should be given here. Although a uniform mix could be obtained when soil or soil-lime is precoated with such amount of mixing water as shown in Table 7, the stabilized mixture of beach sand appears to be so much sensitive that just little disturbance will cause the reduction in the degree of uniformity of the mixture. Thus the mixing process must be stopped immediately as the uniform mixture is obtained, otherwise, the balling of asphalt will be produced. However, as the already prepared mixture of beach sand is disturbed during the molding process, there appears to be no method to prevent the decrease in the degree of the uniformity, hence the compacted stabilized beach sand will finally become non-uniform. This faifure is believed to be because of very poor adhesion between the particles of beach sand and cationic emulsions.

2. Compaction Characteristics

As emulsion is added to a soil, it has important effects on the behaviour of the mixture during compaction and on the voids content. The emulsion will lubricate the soil structure during compaction and help to prevent segregation; it will also fill or partially fill the voids in the soil system. The presence of emulsion, therefore, will cause the changes in the compaction characteristics of soils.

Figures 4 and 5 illustrate the effect of addition of emulsion on the compaction characteristics of silty sand and beach sand. The results show that the presence of emulsion causes an increase in maximum dry density and a decrease in optimum moisture content of both sands. This is undoubtedly because of the effects of emulsion having been described above.

With the same percentage of molding moisture content, the results show that the dry density of soil-emulsion increases with increasing emulsion content. However for the high value of molding moisture content (the wet side of compaction curves), it was found that the dry density of soil-emulsion with higher emulsion content became lower than that with lower emulsion content. This is because of the effect of water contained in the asphalt emulsion. The higher the emulsion content, the greater is the amount of water in the system of soil-emulsion.

When lime is added to a soil, the process of agglomeration or flocculation of clay particles will take place and the soil will

(continued on page 41)

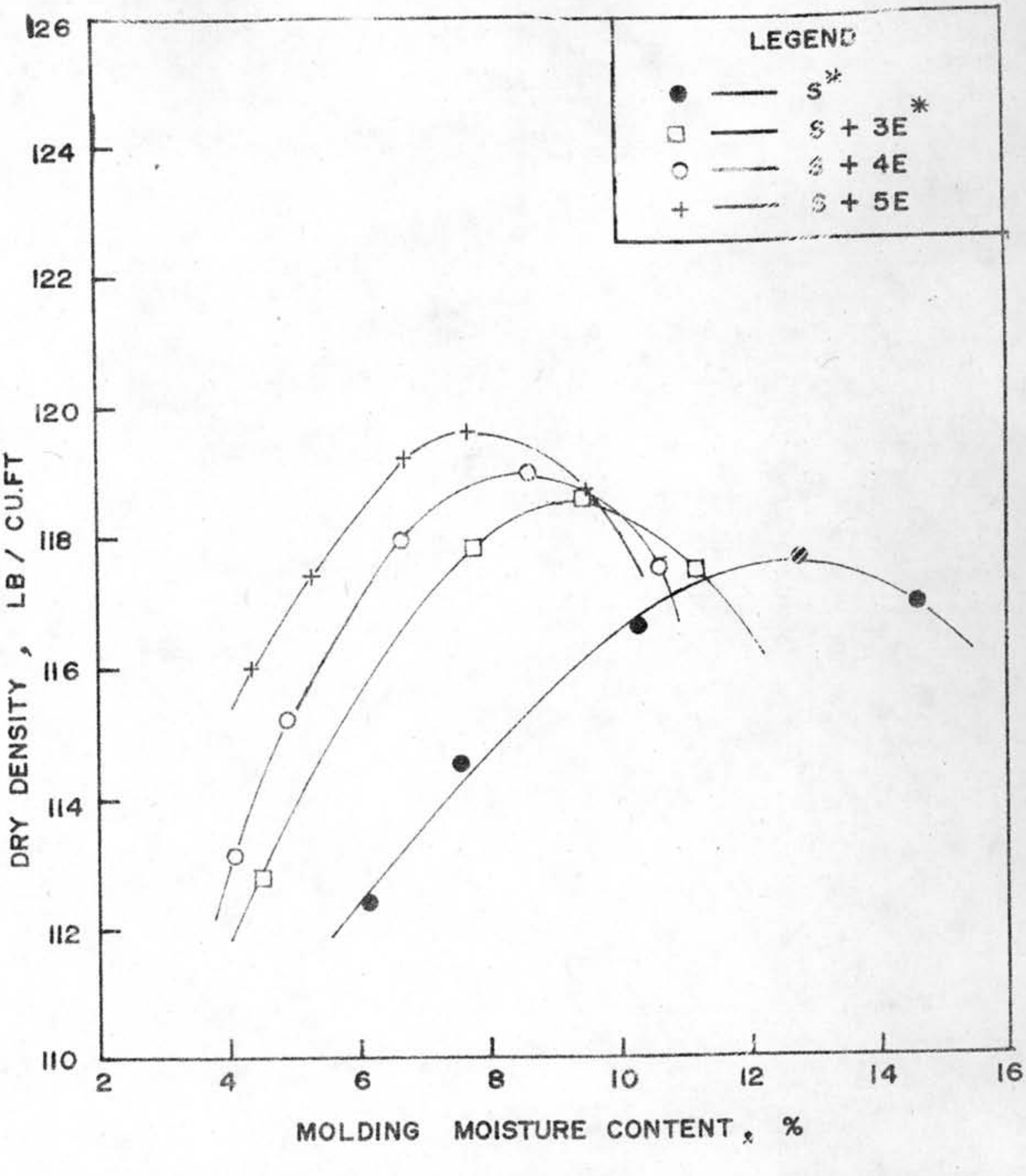

FIGURE 4. COMPACTION CURVES OF SILTY SAND STABILIZED WITH VARIOUS PERCENT EMULSION

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* S : SILTY SAND

S + 3E : SILTY SAND STABILIZED WITH 3% EMULSION

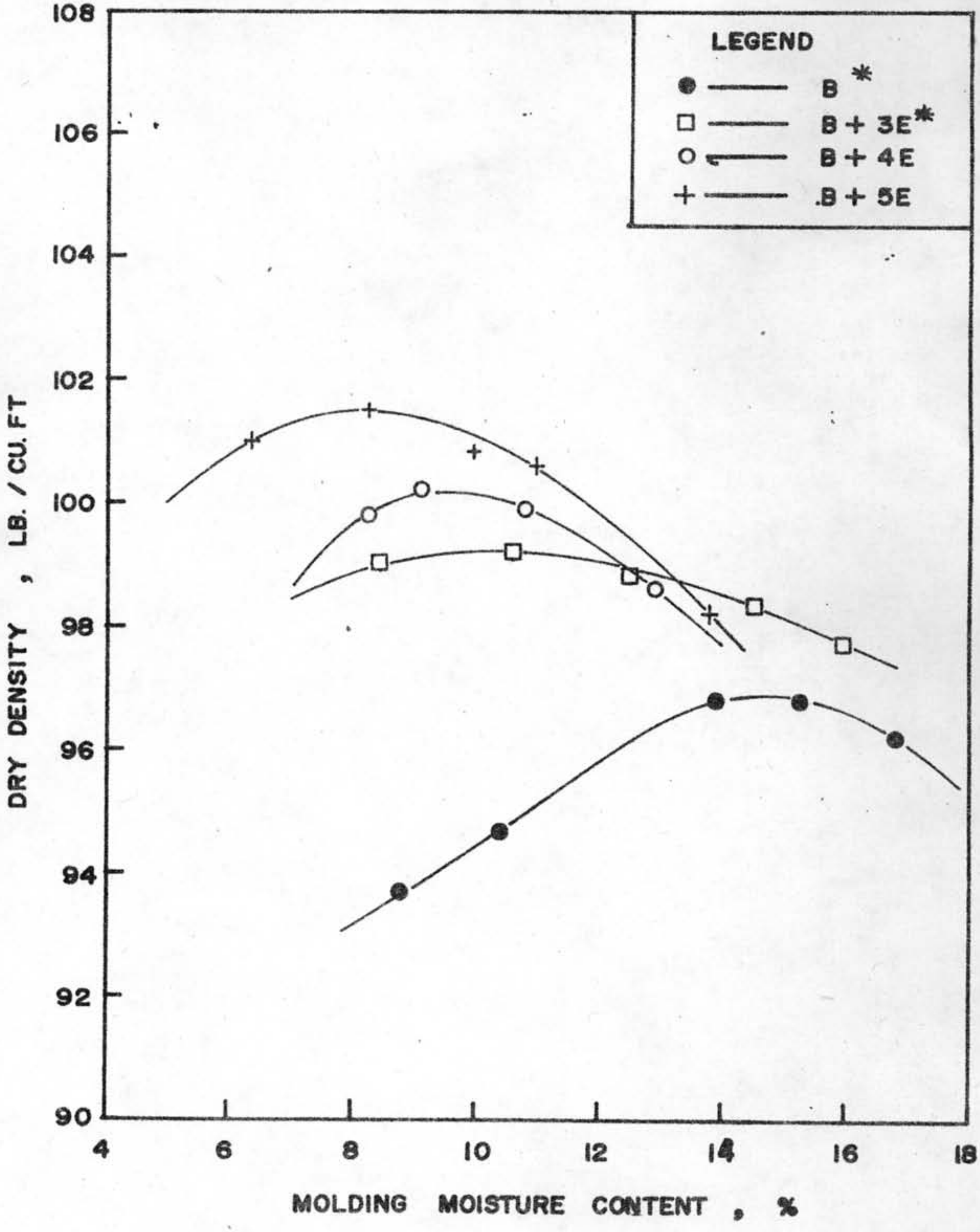

FIGURE 5. COMPACTION CURVES OF BEACH SAND STABILIZED WITH VARIOUS PERCENT EMULSION

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B : BEACH SAND

B + 3E : BEACH SAND STABILIZED WITH 3% EMULSION become coarser and more friable. Thus the added lime will cause the change in the compaction characteristics of a soil. The decreases in the maximum dry density and increases in optimum moisture content usually occur with the presence of lime. In this study, the results in Fig.6 show that addition of lime tends to increase the maximum dry density of silty sand instead of decreasing as usual in the other soils. This may be explained by the fact that as the soil-lime mixture is compacted immediately after mixing, lime tends to act as filler materials rather than to react with clay particles in silty sand. So, adding lime into silty sand will result in improving the grain size distribution and thus higher density could be obtained. However, Figure 6 shows that addition of lime to silty sand has no effect on the optimum moisture content. The compaction curves of silty sand and beach sand stabilized with 3% lime and various percent emulsion are shown in Fig. 6 and Fig. 7. The effect of emulsion on the compaction characteristics of soil-lime mixture is found to be similar to that when emulsion is added to soil without lime.

As shown in Fig. 8 and Fig. 9, moisture-density curves of soils and soil-cement with various percentages of emulsion were plotted. The results show that addition of cement to silty sand increases the maximum dry density and decreases the optimum moisture content. Similar to soil-emulsion, soil-cement-emulsion appears to give higher density and decrease the optimum moisture content when the emulsion content is increased. By comparing the results presented in Figures 8 and 9 to those in Figures 4 and 5, it can be clearly seen that the maximum density of soil-emulsion is increased when 3% cement is added;

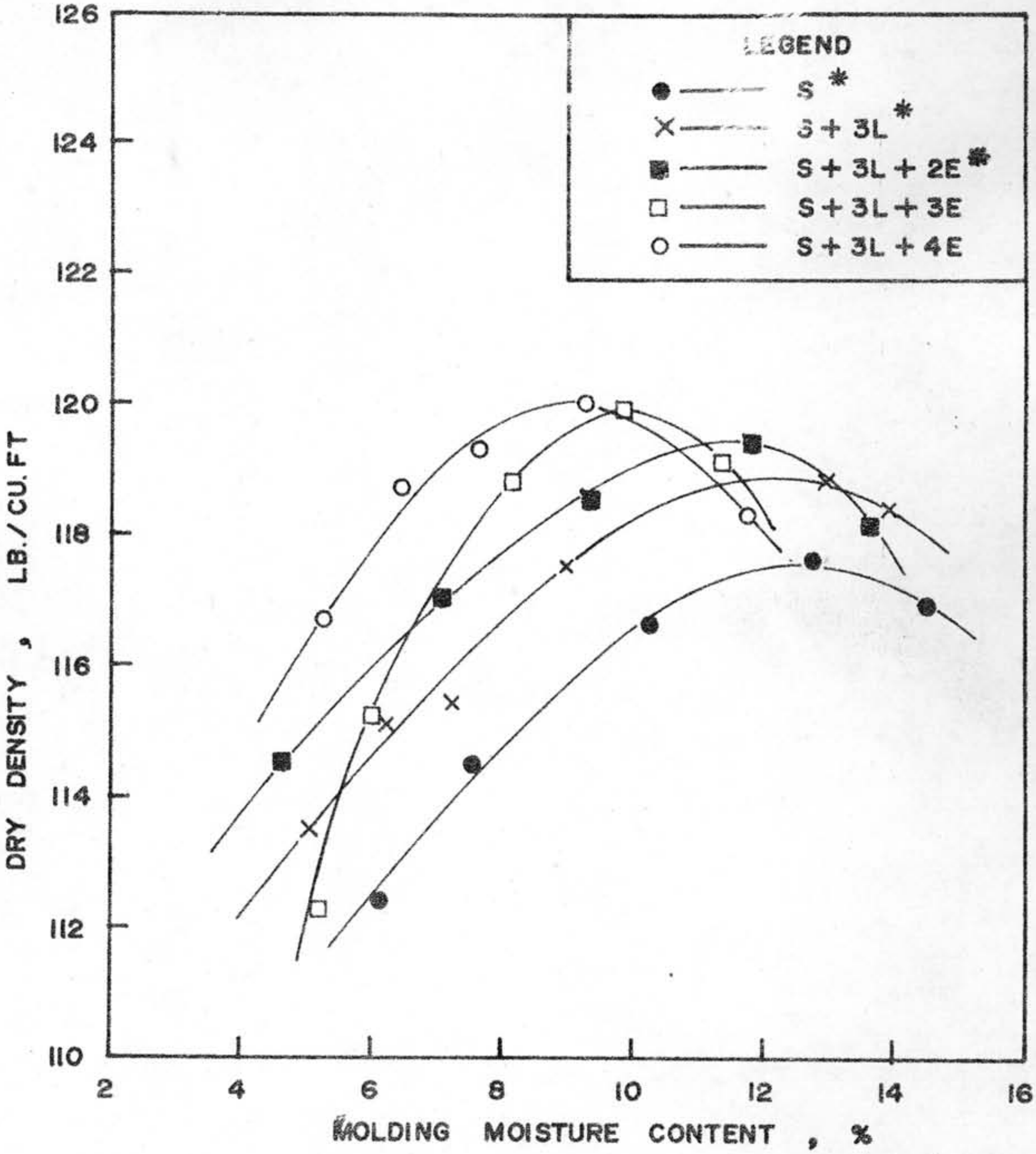

FIGURE 6. COMPACTION CURVES OF SILTY SAND STABILIZED WITH 3 PERCENT LIME AND VARIOUS PERCENT EMULSION

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* S : SILTY SAND

S + 3L : SILTY SAND STABILIZED WITH 3% LIME

S + 3L+2E: SILTY SAND STABILIZED WITH 3% LIME AND 2% EMULSION

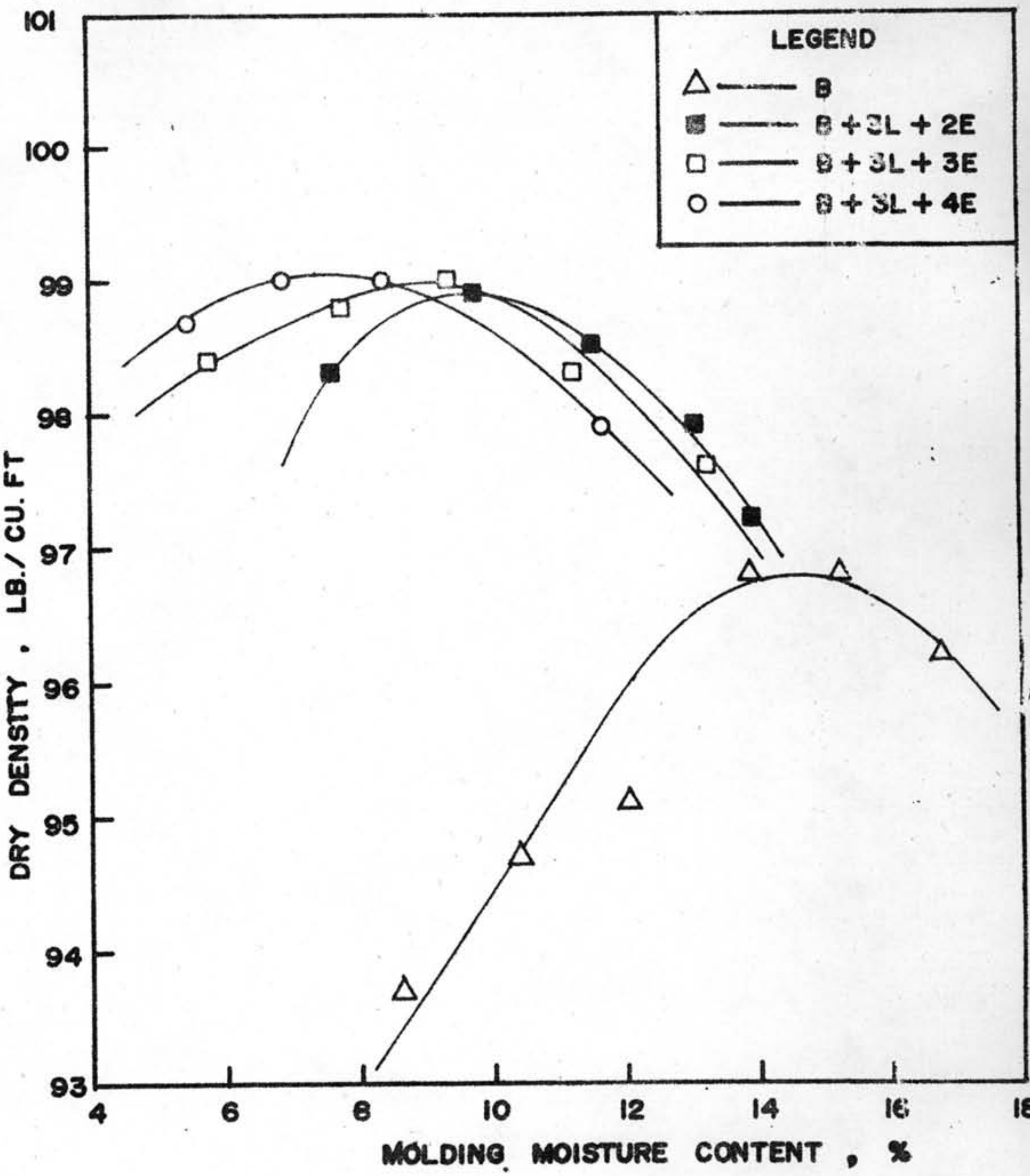

FIGURE 7. COMPACTION CURVES OF BEACH SAND STABILIZED WITH 3 PERCENT LIME AND VARIOUS PERCENT EMULSION.

B BEACH SAND

B + 3L + 2E: BEACH SAND STABILIZED WITH 3% LIME AND 2 % EMULSION

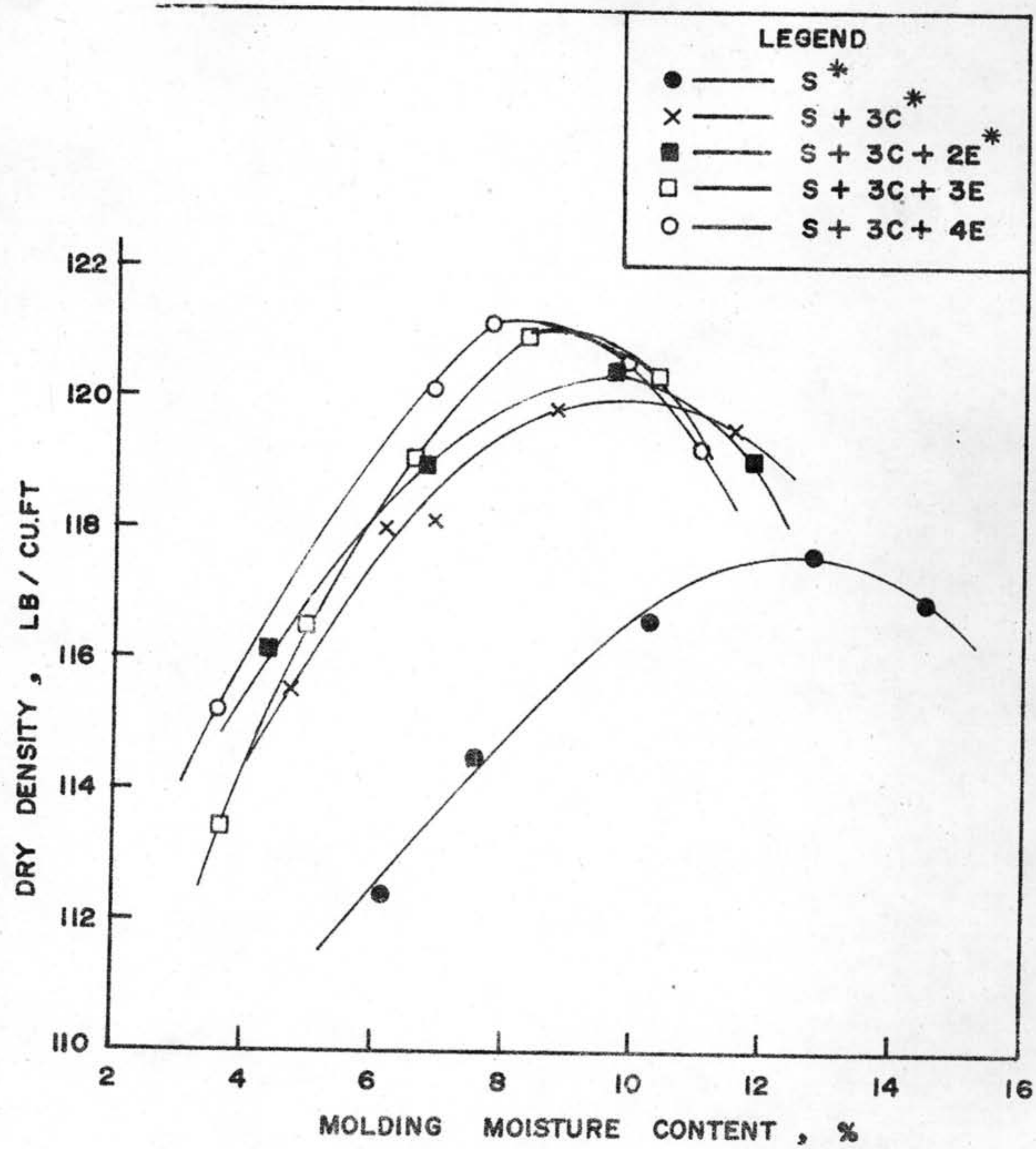

FIGURE 8. COMPACTION CURVES OF SILTY SAND STABILIZED WITH 3 PERCENT CEMENT AND VARIOUS PERCENT EMULSION

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* S : SILTY SAND

S+3C : SILTY SAND STABILIZED WITH 3% CEMENT

S.+3C+2E : SILTY SAND STABILIZED WITH 3% CEMENT AND 2% EMULSION

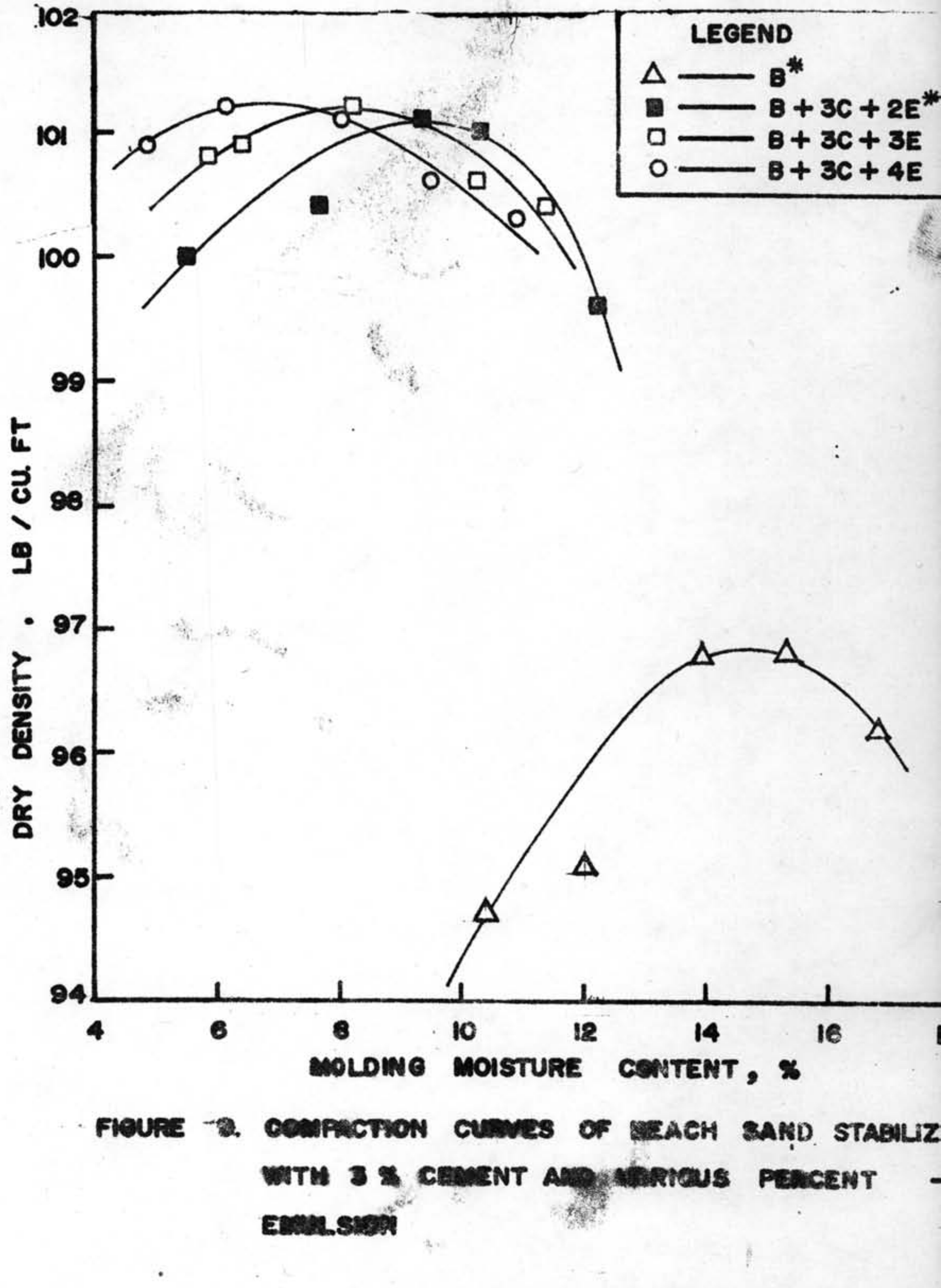

FIGURE 3. COMPACTION CURVES OF BEACH SAND STABILIZ
WITH 3 % CEMENT AND VARIOUS PERCENT
EMULSION

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* : B BEACH SAND

B+3C+2E BEACH SAND STABILIZED WITH 3 % CEMENT AND 2 % EMULSION this is true for both silty sand and beach sand.

3. Unconfined Compressive Strength VS. Molding Moisture Content

Various mix samples of soil-emulsion, soil-lime-emulsion, and soil-cement-emulsion were prepared by the method having been stated in Art. 2.5 of Chapter III. The relationship between unconfined compressive strength and molding moisture content were determined and the results are shown in Figures 10, 11 and 12. Although two kinds of sandy soils were used in this study, unfortanately, only the results for silty sand conld be obtained and presented in the figures. As previously reviewed, the stabilized mixture of beach sand tends to lose the uniformity of asphalt distribution when being disturbed by the compacting effort during the molding process. Theorfore, with small proportion of emulsion, the cohesive strength of stabilized beach sand was found to be so little that almost every specimen was cracked and disintigrated immediately as it was extruded out of the mold. With the presence of 3% lime in soil-emulsion system, it appears that no specimen could be prepared though the relatively large amount of emulsion was used. For this reason only the specimens of some types of mix of beach sand could be successfully prepared, such as beach sand with emulsion of the percentages higher than 4, and beach sand plus 3% cement with emulsion of the percentages higher than 3. These already prepared specimens, however, were found to possess little or no compressive strength when they were subjected to the unconfined compression test. Owing to these problems, the relationship between unconfined compressive strength and the molding moisture content for stabilized beach sand could not be determined and presented in this study. For silty sand, the results in Figure 10 show

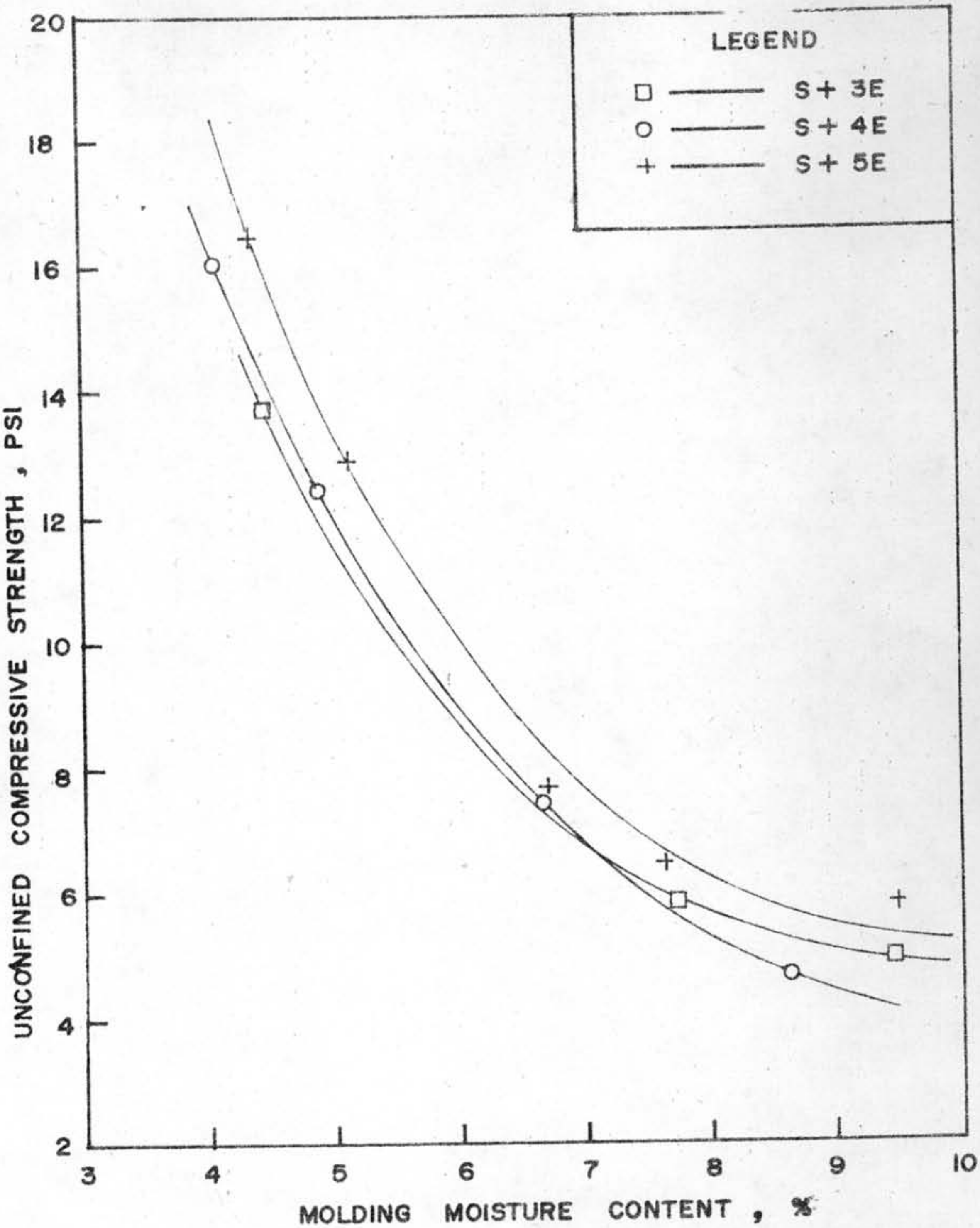

FIGURE 10. RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND MOLDING MOISTURE CONTENT OF SILTY SAND WHEN STABILIZED WITH VARIOUS PERCENT EMULSION

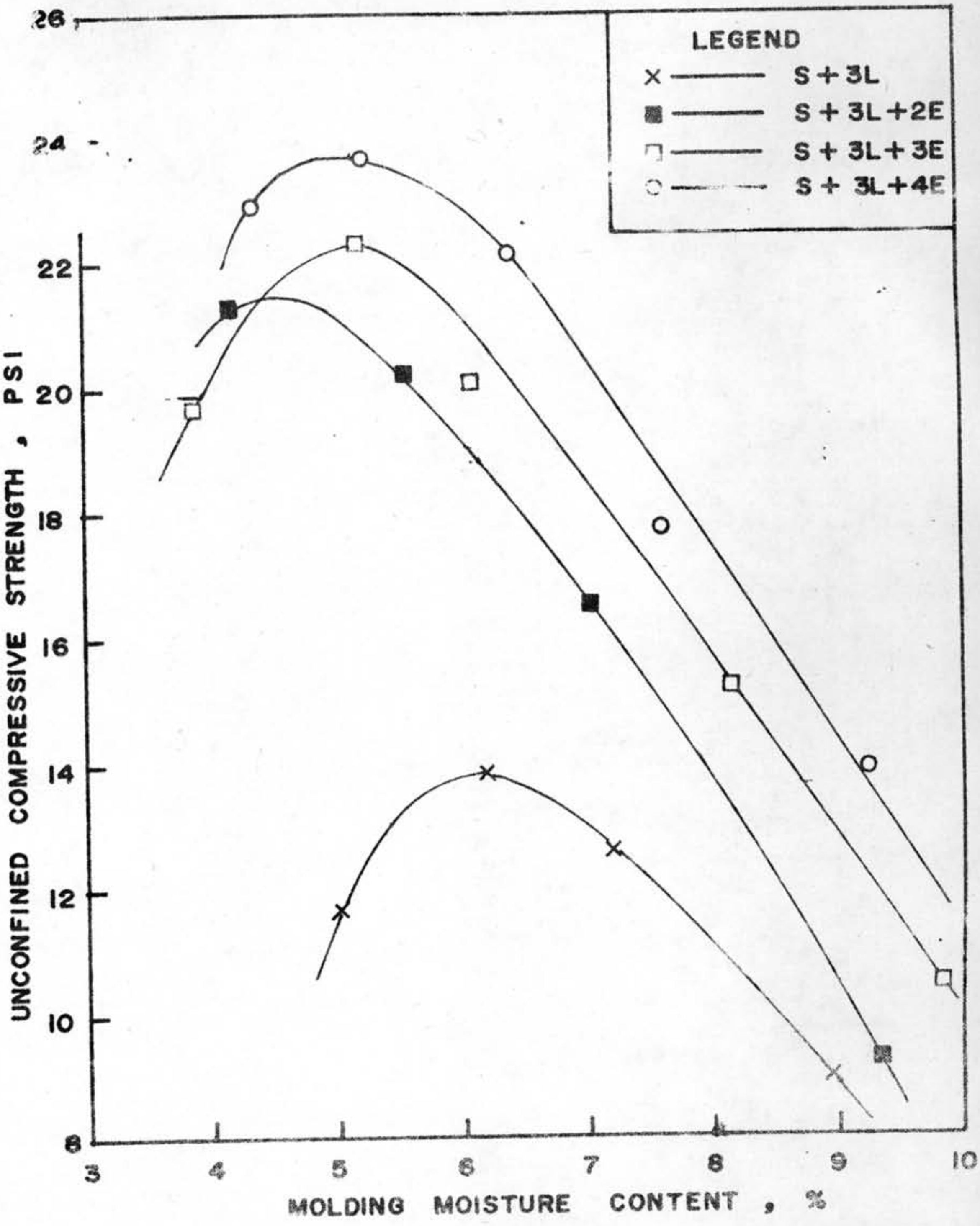

FIGURE 11. RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND MOLDING MOISTURE CONTENT OF SILTY SAND WHEN STABILIZED WITH 3 PERCENT LIME AND VARIOUS PERCENT EMULSION

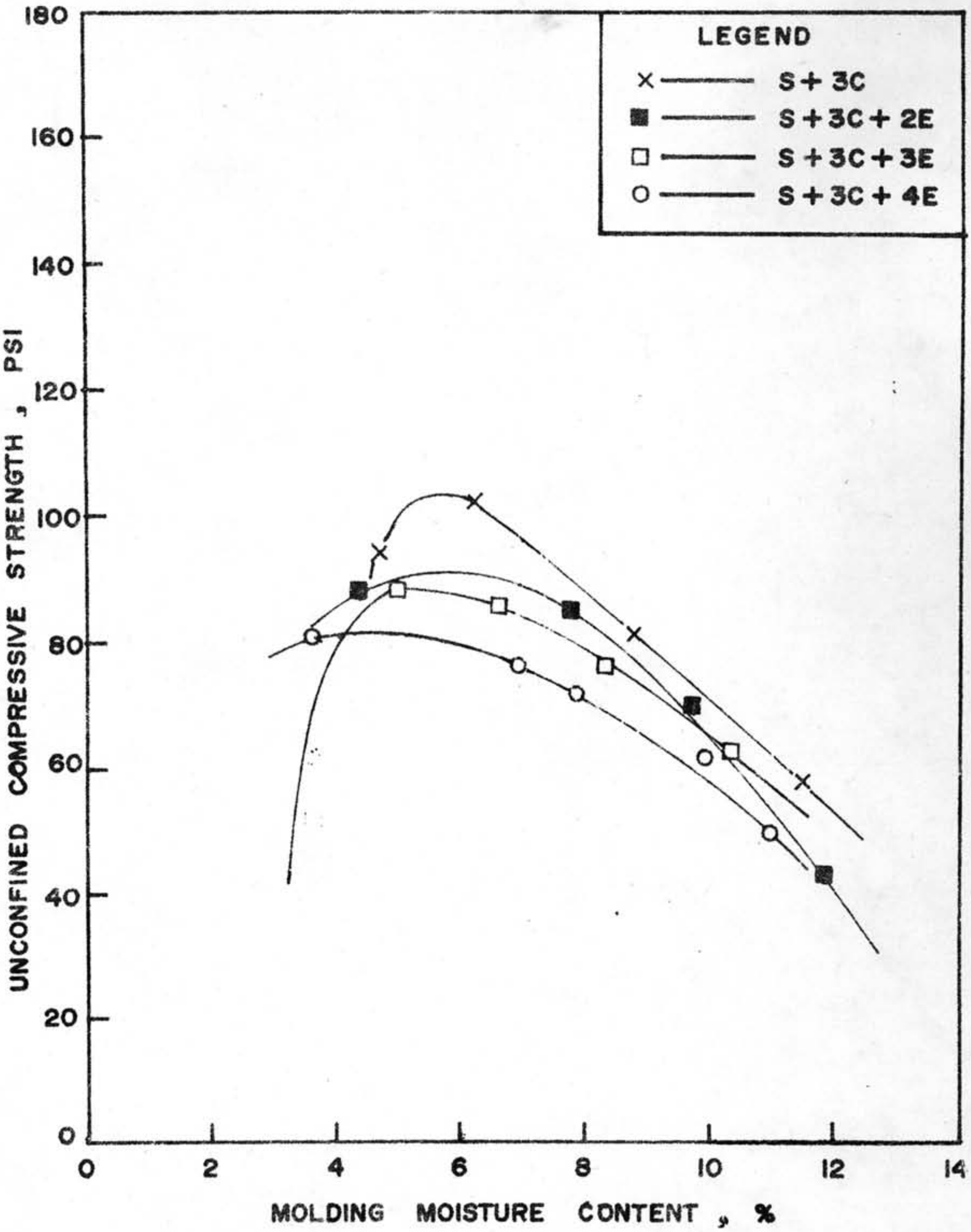

FIGURE 12. RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND MOLDING MOISTURE CONTENT OF SILTY SAND WHEN STABILIZED WITH 3 PERCENT CEMENT AND VARIOUS PERCENT EMULSION

that the moisture content of the compacted specimens have significant effect on the compressive strength of soil-emulsion, whereas there appears to be no relationship between the strength and the dry density to which the specimens were compacted. With the same percentage of emulsion, only small values of unconfined compressive strength could be measured when the specimens were prepared by using high percentage of molding moisture content. As the value of molding moisture content was reduced, the unconfined compressive strength was found to be increased; and with the further reduction in molding moisture content, the strength tends to be increased even more. Although the addition of water to silty sand before being mixed with emulsion can provide good dispersion of asphalt throughout the soil system, the presence of water in the compacted specimen appears to lubricate the soil particles and thus cause the decrease in shear strength.

As stated in Chapter II, for a given set of conditions, the diffence in emulsion content will result in changing the strength of emulsion - stabilized sand. In general, the higher strength can be obtained by increasing the percentage of emulsion. However, when the emulsion content reaches a certain value known as optimum emulsion content, the strength will be no longer increased. At this point, the maximum strength of soil-emulsion will be obtained; and with the higher value of emulsion content, the reduction in the strength will take place. Unfortunately, for the sake of economical design, no test was performed in this study with emulsion content higher than 5%. As shown in Fig. 10, the unconfined compressive strength of silty sand with 5% emulsion is slightly higher than that of silty sand with

4 and 3% emulsion.

For soil-lime-emulsion and soil-cement-emulsion, Figures 11 and 12 show that the unconfined compressive strength for each type of mixes of stabilized silty sand is influenced not only by the molding moisture content but also by the dry density. As same as for soil-emulsion, the decrease in molding moisture content causes the increase in strength. However, to a certain value the molding moisture content is reduced, the unconfined compressive strength appears to be increased no more. This value of molding moisture content for each type of mixes is found to be on the dry side of the optimum moisture content at which the maximum dry density is obtained. The decrease in strength with the further reduction of the molding molding content is considered to be because of the relatively low density of the compacted specimen which affects the cementing action of lime or cement. As shown in Figs. 10, 11 and 12, it can be clearly seen that with the same percentage of stabilizer of 3%, soil-cement gives much higher strength than soil-lime and soil-emulsion. The results indicate that the addition of emulsion into soil-lime system not only provides the waterproofing property, but also causes the increase in shear strength. The emulsion content seems to have same effect on the strength property of soil-lime-emulsion as of soil-emulsion. However, for soil-cement emulsion, when 3% cement was added to soil-emulsion, the strength tends to be lower than when the same amount of cement was added to soil alone. The higher the emulsion content, the smaller is the strength of soil-cement-emulsion. This can be explained by the fact that with the presence of emulsion, the soil particles of silty sand will be partially coated with asphalt and thus some part of cementing action will be prevented. This effect is more pronounced as the higher percentage of emulsion is applied.

4. Emulsion Stabilization

As mentioned in the previous chapter, in selecting the suitable moisture content for molding the specimens, the test results for the relationship between unconfined compressive strength and molding moisture content should be considered. For each mix, the moisture content giving a maximum strength should be selected to mold the specimens. However, in the case of silty sand stabilized with emulsion, as shown in Fig. 10, the test result did not show a peak value of the unconfined compressive strength. For stabilized beach sand, as has been stated in the previous section, no test for unconfined compressive strength could be carried out. According to these problems, the range between 6 and 7 percent of moisture content were considerably selected to mold the specimens for various mix of this type of stabilization. The specimens were prepared, cured, and tested by using the methods explained in Art. 2.6 of the previous chapter. All detailed test results are given in Appendix B and Appendix C. In this chapter, only the significant experimental results are presented and discussed.

4.1 Effect of Emulsion on Strength Parameters Cu and ϕ_u

As reviewed in Chapter II, addition of emulsion has the effect of giving unconfined sand some cohesive strength and at the same time reducing the angle of shearing resistance. In general, for a given set of conditions, the increase in cohesive strength and reduction in angle of shearing resistance will take place as the percentage of emulsion is increased. By using silty sand and beach sand, the results obtained in this study seem to show the similar trend.

Fig. 13 shows the effect of the addition of emulsion upon the strength parameters Cu and ϕ_u of silty sand. The result for silty sand with 5% emulsion presented in the figure were obtained from those specimens cured in sealed platic bags for 7 days.

It appears that silty sand itself exhibits no cohesive strength. The presence of 5% emulsion causes the value of Cu to increase from 0 to 12.5 psi. However, the angle of shearing resistance of silty sand was found to be decreased by three degrees as 5% emulsion was applied. This points out that the strength parameters Cu and ϕ_u of silty sand are affected by emulsion in a similar manner as usual for the other sands.

Unfortunately, according to the problem in preparing the specimens, the strength parameters for untreated beach sand could not be determined. Thus the effect of emulsion on the stength parameter Cu and ϕ_u of beach sand could not be clearly evaluated in the present study.

Fig.14 illustrates the changes in Cu and ϕ_u of stabilized silty sand and stabilized beach sand due to varying emulsion content. Undonbtedly for silty sand, increase in emulsion content results in increasing the value of Cu and reducing the value of ϕ_u. For beach sand, the result shows that with 4% emulsion, the cohesion intercept Cu has not developed, whereas a small value could be measured from the specimens with 5% emulsion.

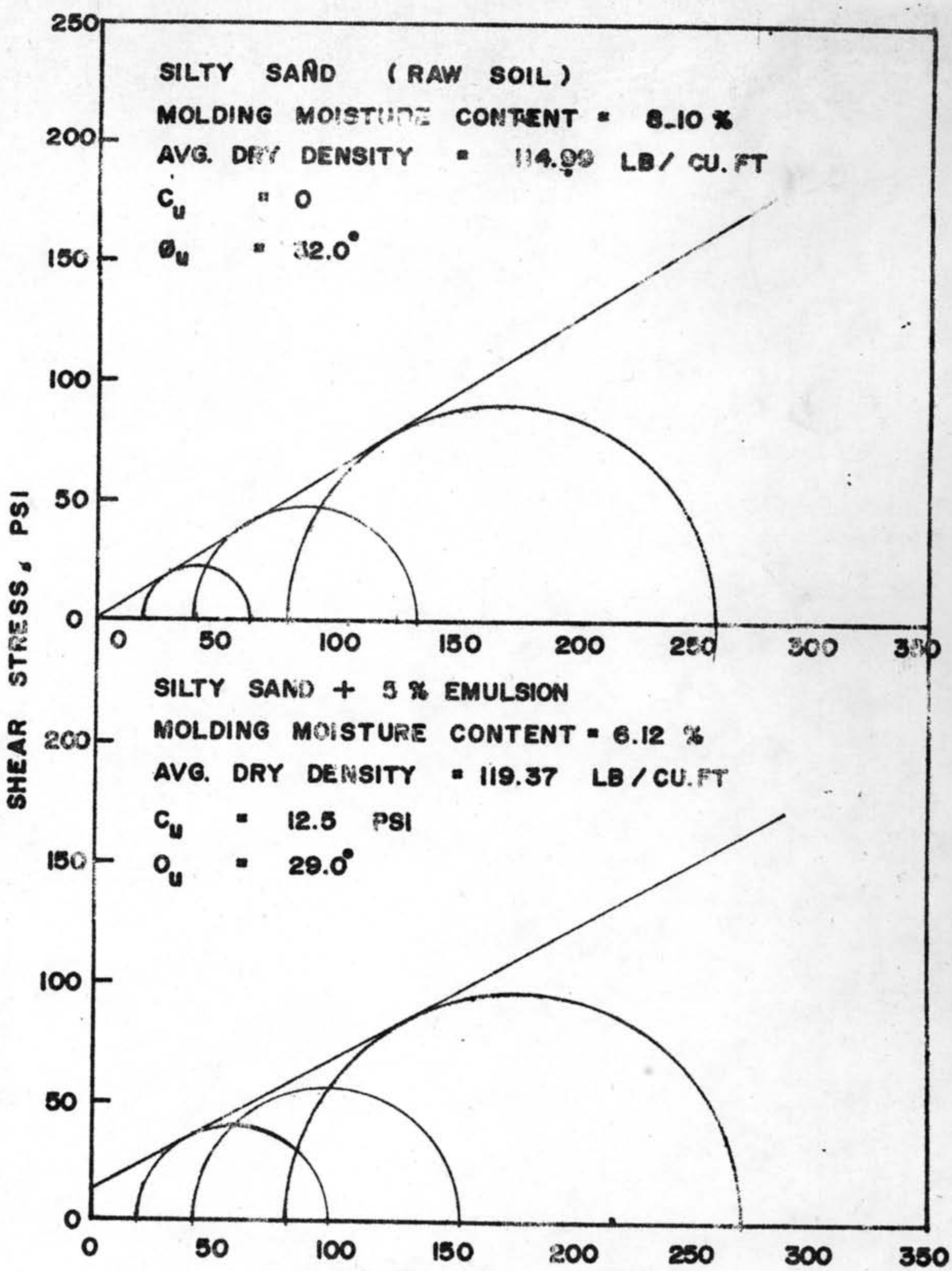

FIGURE 13. TYPICAL MOHR CIRCLE OF RAW SOIL AND SOIL – EMULSION

CURING TIME = 7 DAYS

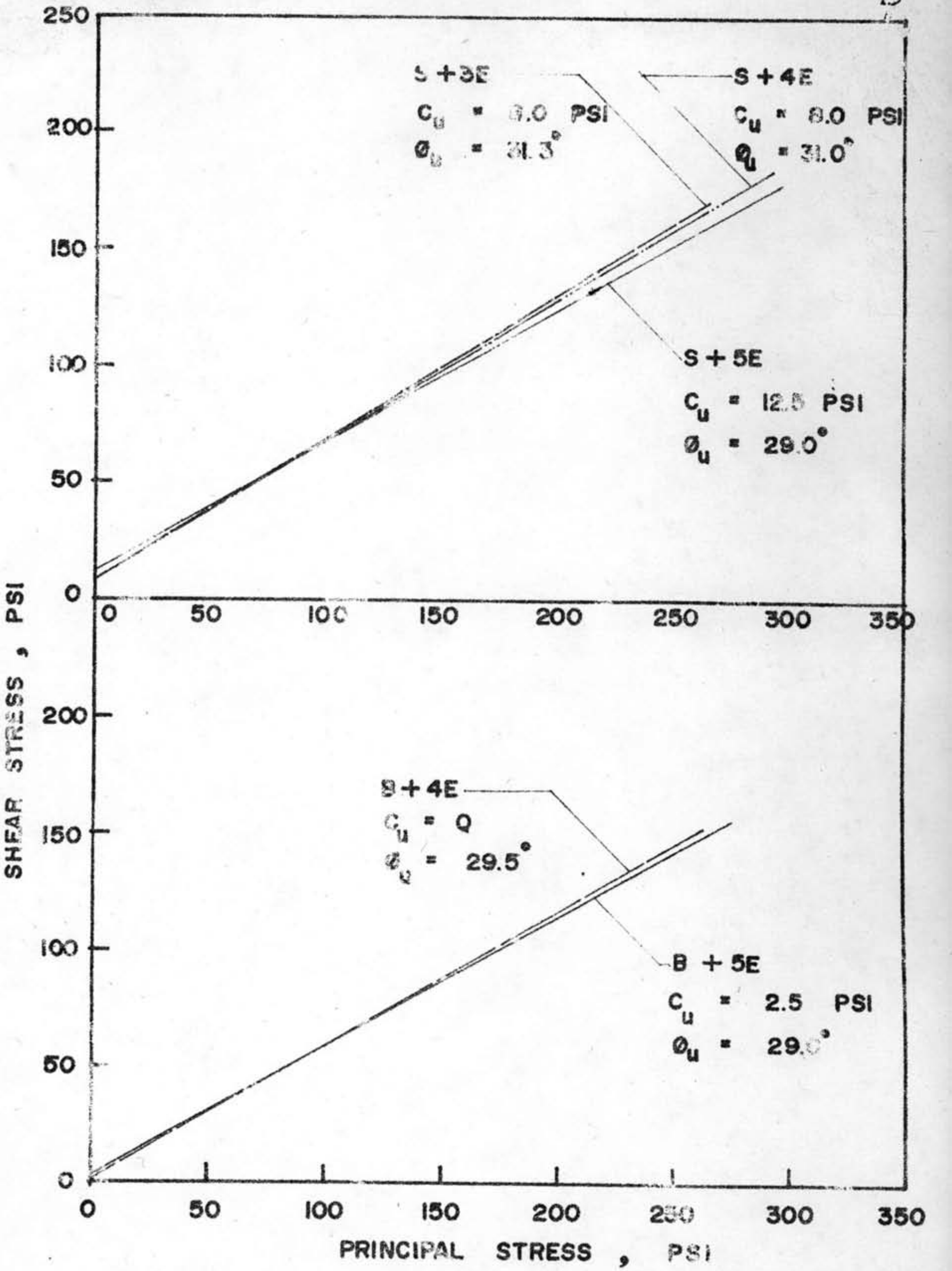

FIGURE 14. MOHR ENVELOPES OF SILTY SAND AND BEACH SAND STABILIZED WITH VARIOUS PERCENT EMULSIO[N]

CURING TIME = 7 DAYS

By comparing the results for silty sand and beach sand as shown in Fig. 14, it can be concluded that the addition of emulsion has much more significant effect upon the strength parameters Cu and ϕ_u of sity sand than those of beach sand.

4.2 Effect of Curing Time on Strength of Soil-Emulsion

The unconfined compressive strength and the strength parameters Cu and ϕ_u silty sand with various percent emulsion are plotted against the curing time as shown in Figures 15 and 16. In the case of beach sand, as has been discussed in Art. 3 this chapter, little or no unconfined compressive strength could be measured from the specimens of stabilized beach sand. Therefore in this study, only the undrained triaxial test was employed to evaluate the effect of curing time on the value of Cu and ϕ_u of beach sand stabilized with 4 and 5 percent emulsion. The results are shown in Fig. 17.

It should be noted here that all specimens of stabilized silty sand and beach sand for this study were cured in sealed plastic bags at room temperature. By this method of curing, it was expected that the evaporation of moisture in the compacted specimens could be prevented. However, as shown in Appendix C, the moisture content retained in the specimens after test were found to be somewhat less than the molding moisture content. The difference between the molding moisture content and the moisture content measured after test was found to be slightly larger with longer period of curing. Some further discussion about this will be presented later in Art. 4.3 of this chapter.

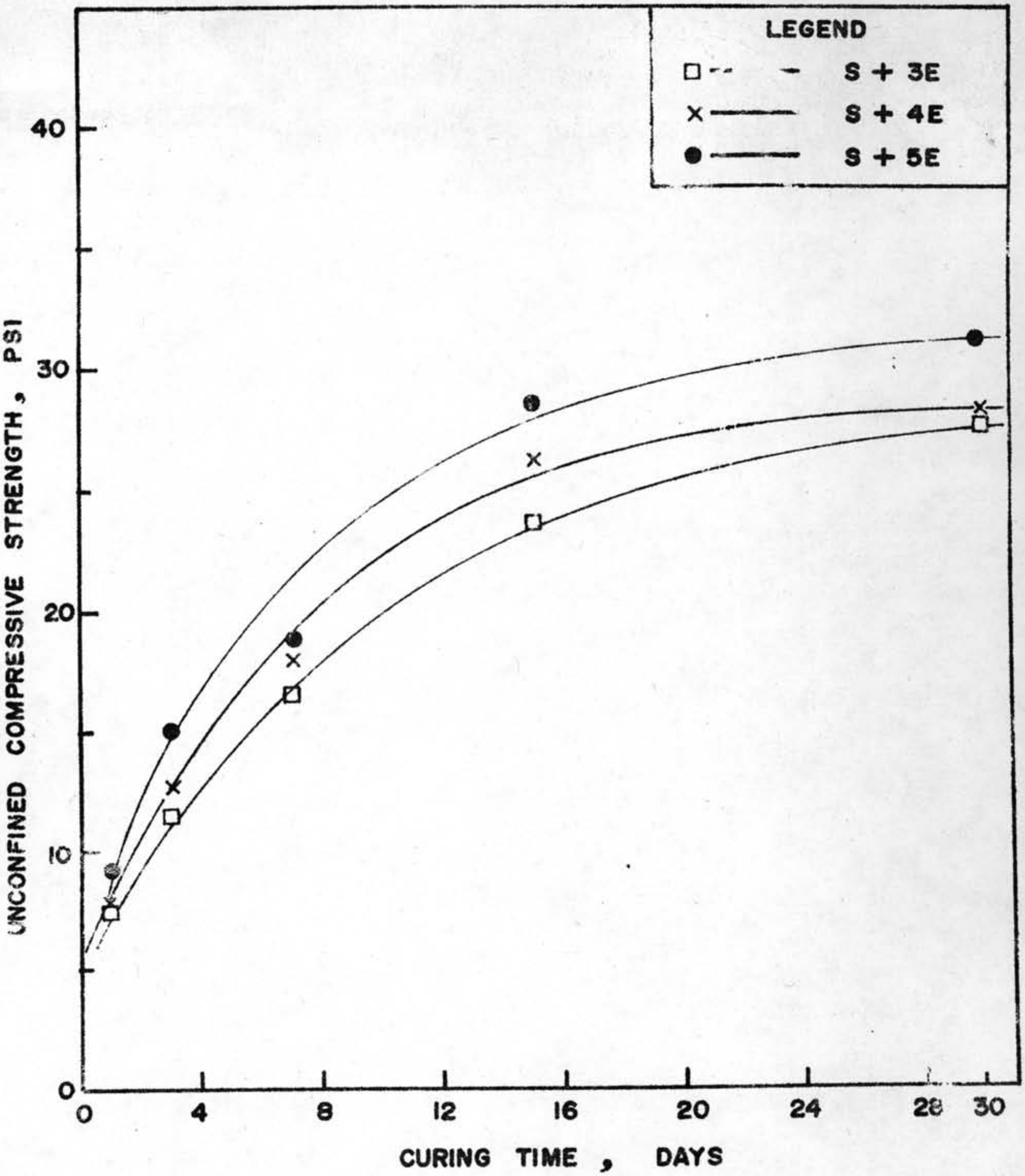

FIGURE 15. UNCONFINED COMPRESSIVE STRENGTH VS. CURING TIME FOR SILTY SAND WITH VARIOUS PERCENT EMULSION

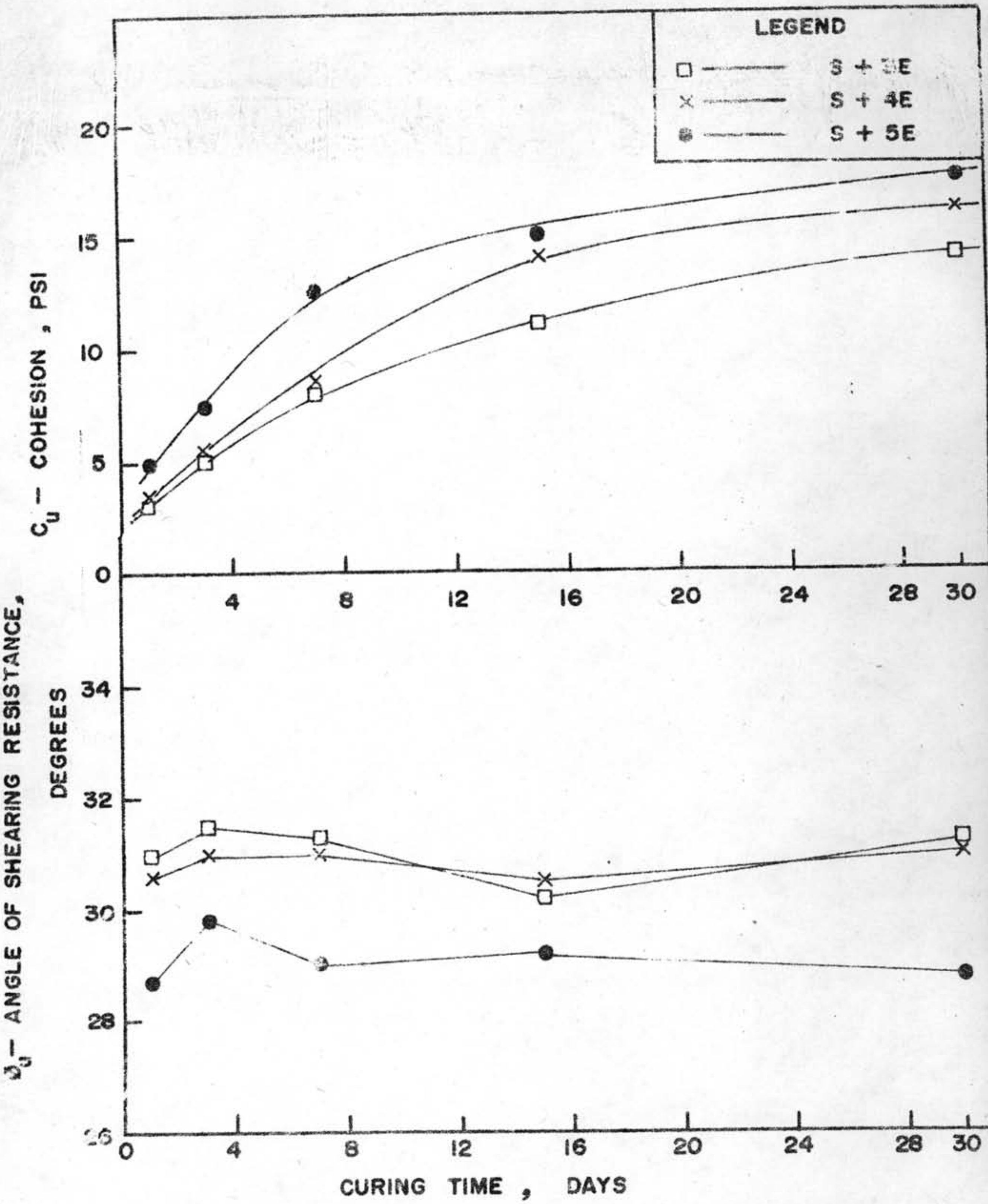

FIGURE 16. COHESION AND ANGLE OF SHEARING RESISTANCE VS. CURING TIME FOR SILTY SAND WITH VARIOUS PERCENT EMULSION

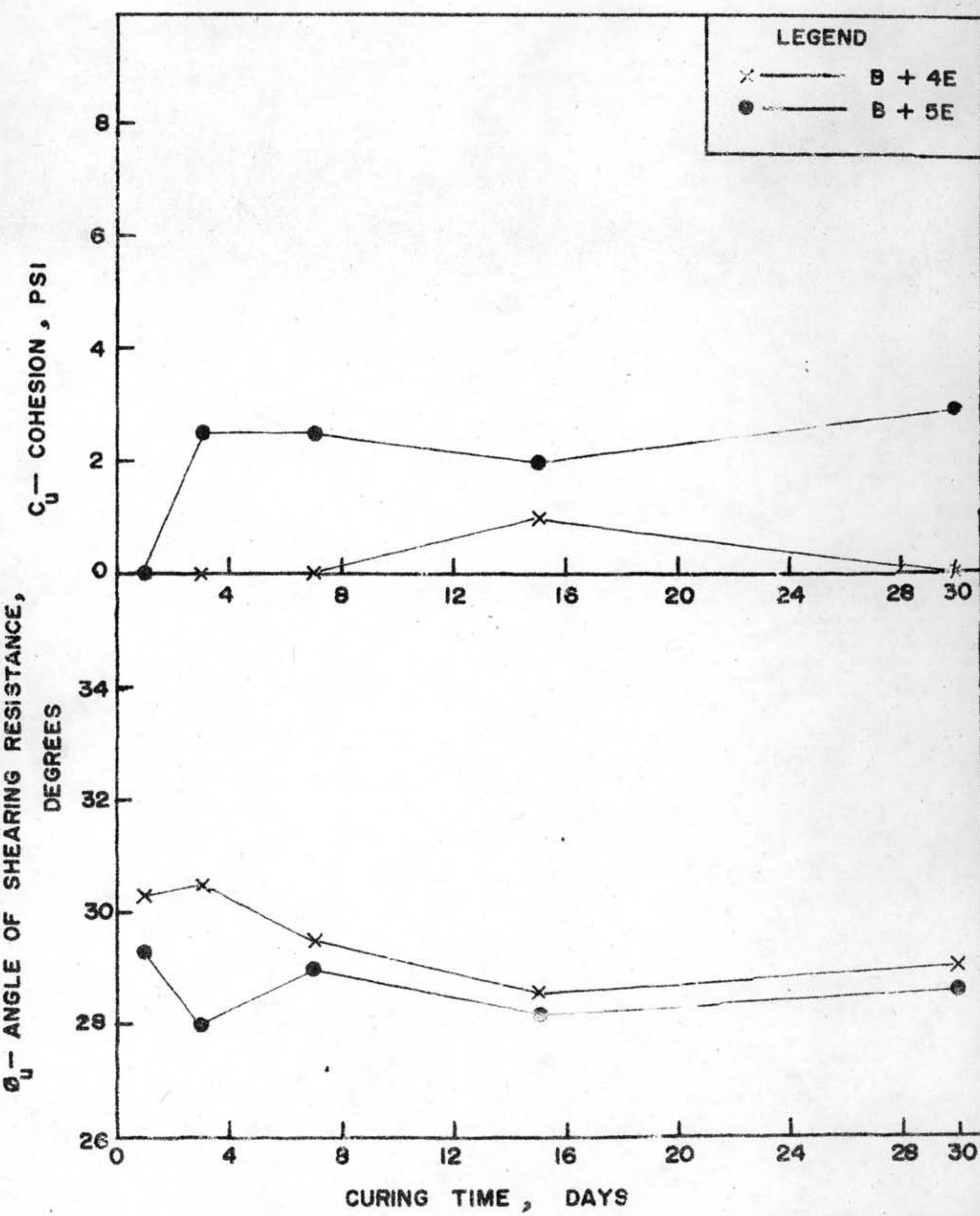

FIGURE 17. COHESION AND ANGLE OF SHEARING RESISTANCE VS. CURING TIME FOR BEACH SAND WITH VARIOUS PERCENT EMULSION

As shown in Fig. 15, the strength development of the specimens of silty sand with 3% emulsion are in a similar manner as those of silty sand with 4% and 5% emulsion. For each emulsion content, the rate of strength increase was found to be faster during the early curing period and then became slower with longer curing time. For one-day curing period, it was found that the unconfined compressive strength of silty sand with 3% emulsion (S+3E) was nearly equal to those of silty sand with 4% emulsion (S+4E). This is due to the fact that the molding moisture content used for preparing the specimens of S+3E was slightly less than the value used for preparing the specimens of S+4E. Such effect of molding moisture content has already been explained in Art. 3 of this chapter. However, with longer curing time, the effect of increasing emulsion content appears to be more significant, thus, the strength of S+4E was finally higher than of S+3E after curing for longer time.

In Figure 16, it is apparent that the value of Cu of silty sand with emulsion increases with increasing curing time. The increasing rate is nearly the same for each emulsion content. By comparing the curves plotted for the values of Cu in Fig. 16 to those in Fig. 15, it can be seen that the increase in Cu are similar to the development of the unconfined compressive strength.

For each type of mix, although the values of ϕ_u were different when measured at different curing period, there appears to be a tendency that the angle of shearing resistance does not depend on the curing time. The result shows that adding 5% emulsion to silty sand causes the angle of shearing resistance to decrease from 32.0° to 28.7° when measured after curing for one day and then increase to 29.8° after curing for 3 days. But after 7 days, the value of ϕ_u was found to be decreased to 29.0°. With longer curing time, it was found that the 15-day and 30-day values were nearly the same as the 7-day value. The same behaviour was observed for silty sand stabilized with 3% and 4% emulsion. Thus it can be concluded that the curing time has no influence on the value of ϕ_u of silty sand with emulsion.

For beach sand with 4% emulsion (B+4E), as shown in Fig. 17, only 1 lb/in^2 if cohesion intercept was developed after 15 days of curing. With any other curing periods, the specimens of B+4E were found to exhibit no cohesive strength. For B+5E, although some cohesive strength could be measured after curing for 3 days, it was found that with longer curing period, the increase in the value of Cu did not take place. Therefore it may be concluded that emulsion has very little effect in improving the cohesive strength of beach sand; and the strength of emulsion-stabilized beach sand is independent of curing time. This is believed to be because of the loss of the uniformity of stabilized mixture of beach sand during the molding process which results in producing the balling of asphalt. Thus, there was a little or maybe no asphalt left to serve as a binder.

As same as for silty sand, the angle of shearing resistance of stabilized beach sand is independent of the curing time. However, it was found that the emulsion content has some effect on the angle of shearing resistance. The higher emulsion content in stabilized beach sand results in smaller angle of shearing resistance.

4.3 Effect of Curing Type on Strength of Soil-Emulsion

Figures 18 and 19 are plotted to show the effect of curing type on the unconfined compressive strength and the strength parameters Cu and ϕ_u of soil-emulsion. The results shown in the figures were obtained from the specimens of silty sand with 5% emulsion cured by two different methods, viz., in-sealed-plastic-bag method and air-dried method. The losses of moisture content which took place during the curing and testing processes are also shown in Fig. 18. The decreases in moisture content of the specimens being cured in sealed plastic bags indicate that the evaporation of moisture could not be perfectly prevented by this method of curing. This is because there was some spacing inside the plastic bag, which enabled the moisture to evaporate from the specimen. This evaporated water, however, could not escape from the sealed plastic bag. Therefore, only small amount of moisture in these specimens were reduced when this curing type was employed.

By air-dried curing, it appears that the rate of evaporation is very rapid at the beginning of curing and becomes slower with increasing curing time. The test results show that after 15 days of curing, the water content of the specimens did not change. This points out that all specimens were completely air-dry and no further evaporation took place after that time.

In the following discussion, for simplicity, the terms "moist specimens" and "air-dried specimens" will be used for the specimens cured in sealed plastic bags and those cured by air-dried method, respectively.

Fig. 18 shows that with the same curing time, the unconfined compressive strength of air-dried specimens of S+5E is much higher

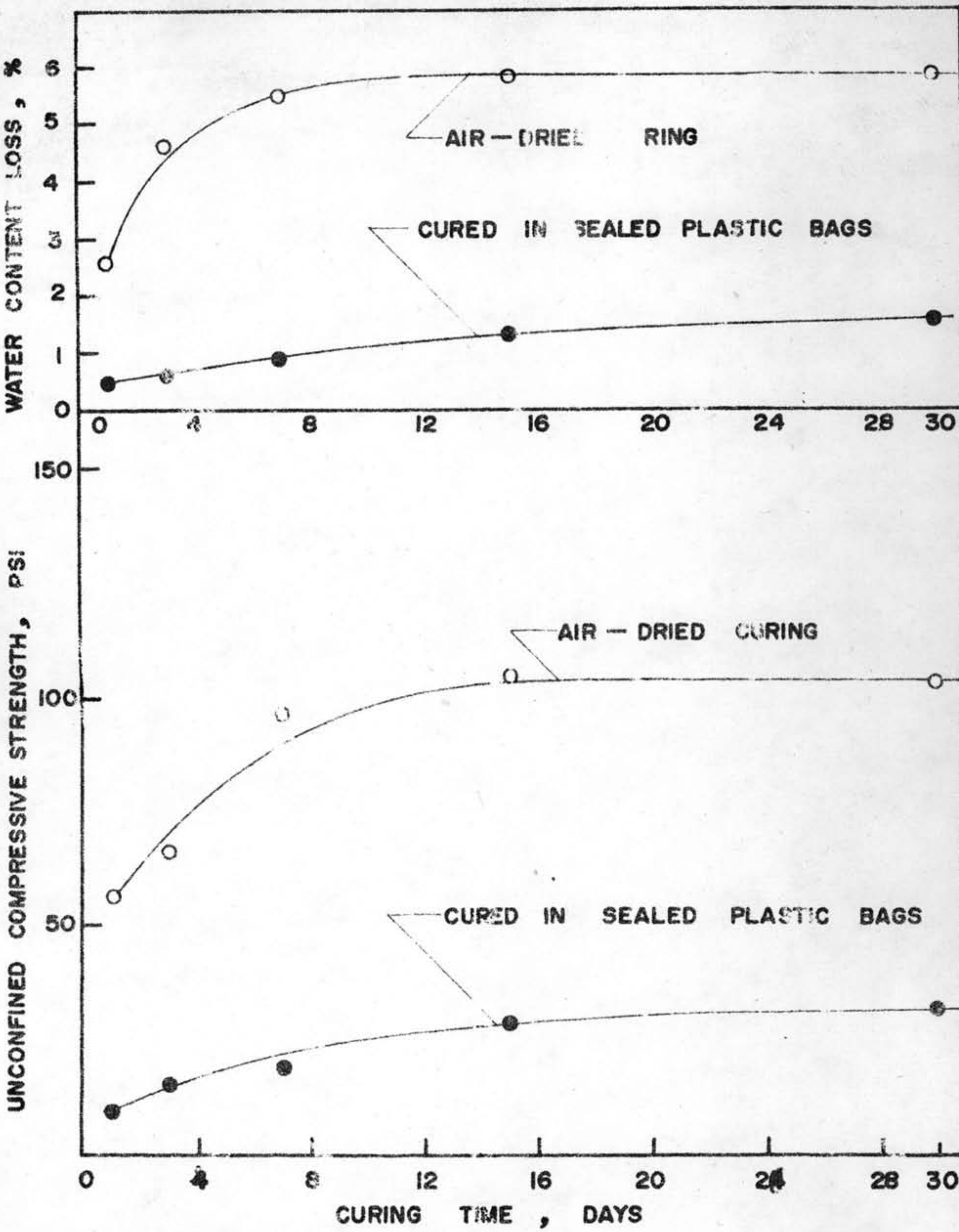

FIGURE 18. EFFECT OF CURING TYPES ON SHEAR STRENGTH OF SOIL — EMULSION (UNCONFINED COMPRESSION TEST) (SILTY SAND WITH 5% EMULSION)

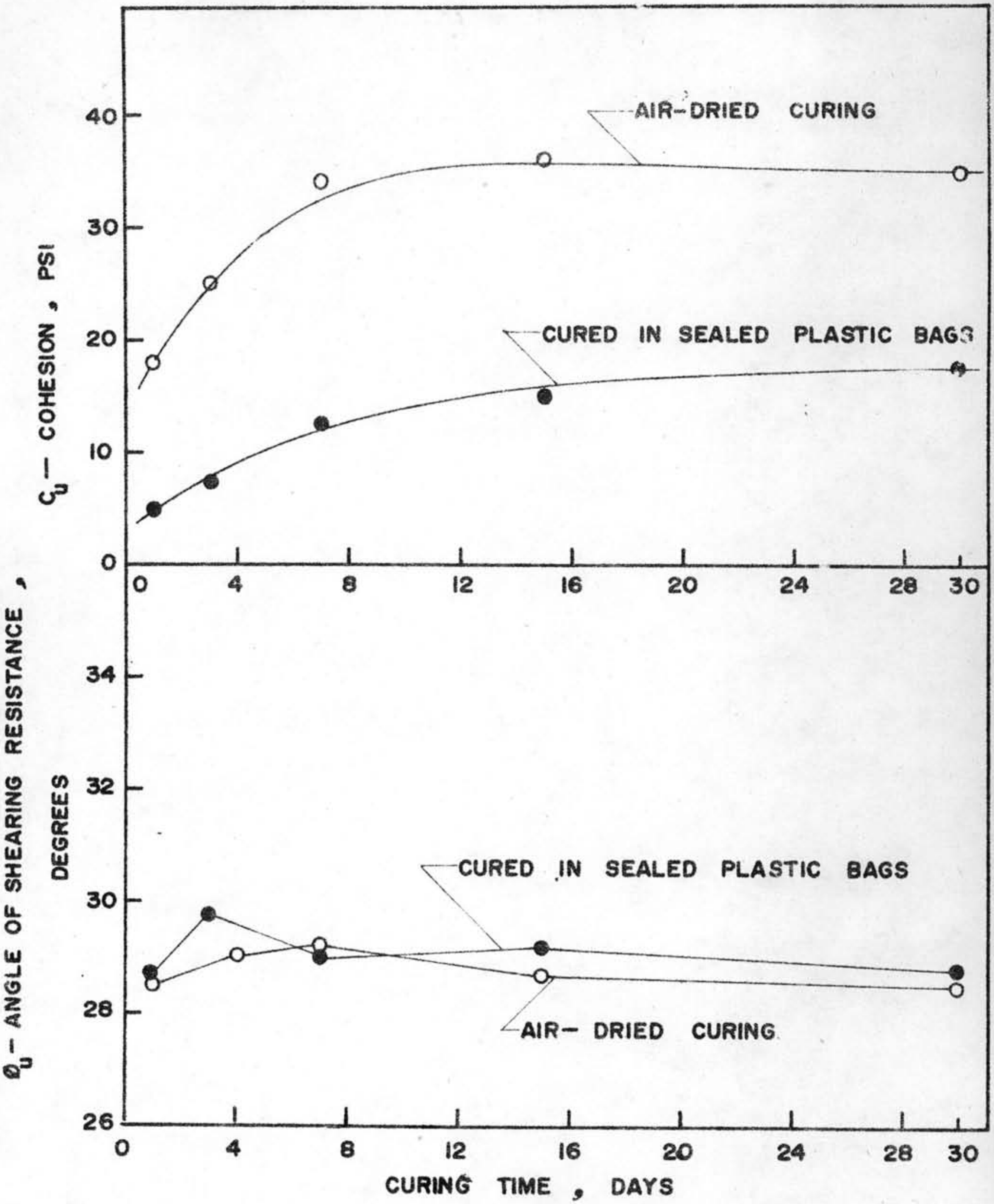

FIGURE 19. EFFECT OF CURING TYPES ON SHEAR STRENGTH OF SOIL — EMULSION (UNDRAINED TRIAXIAL TEST) (SILTY SAND WITH 5 % EMULSION)

than that of the moist specimens. After curing for one day, the air-dried specimens developed strength of about five times of that developed by the moist specimens. With increasing curing time, the rates of strength increase of the two curing methods are also different. The air-dried strength increased rapidly during the first week of curing time. After 7 days of curing, the rate of increase in strength became slower, and a maximum strength was reached within 15-day curing period.

For moist specimens, the strength increasing rate during the first week of curing is relatively slow compared to that of the air-dried specimens. However, after the first week, the strength still gradually increased throughout the entire period of investigation.

As stated in Art. 3 of this chapter, the moisture content retained in the compacted specimens has important effect on the strength of soil-emulsion. As the moisture content of the specimens is decreased, the increase in strength will take place. In other words, the specimens containing smaller amount of water will exhibit higher strength. This seems to be the reason why the strength of air-dried specimens is much higher than that of the moist specimens. Furthermore, the rapid increase in strength at the beginning of curing period is due to the fast rate of moisture evaporation which consequently results in rapid hardening of the specimens. No further development of strength after 15 days of air-dried curing is undoubtedly because of no change in moisture content taking place after that time.

As shown in Figure 19, the curing types tend to affect the development of cohesion intercept (or cohesive strength) of soil-emulsion in a manner similar to that of the unconfined compressive strength. However, it is quite clear from the figure that the angle of shearing resistance is independent of curing types. Therefore it can be concluded that the curing types will affect the cohesive strength of soil-emulsion only, but not affect the angle of shearing resistance.

5. Lime-Emulsion Stabilization

A combination of 3% lime and 3% emulsion was selected to add to silty sand and beach sand for the purpose of studying the strength characteristics of soil-lime-emulsion mixtures. The specimens for this study were prepared, cured and tested by using the method stated in Chapter III. In molding the specimens, the moisture content varying from 6% to 7% was used. This range of molding moisture content is the same as that used in preparing the specimens for soil-emulsion stabilization. By this condition, the results for soil-lime-emulsion and soil-emulsion could be reasonably compared.

Three percent lime alone was also used to stabilize silty sand and beach sand in order to evaluate the effect of lime on strength properties of sandy soils. The specimens for soil-lime were also molded by using approximately the same molding moisture content as for other mixes.

However, it was found that almost every specimen of stabilized beach sand was cracked after being extruded from the compaction mold. Therefore, only the results for stabilized silty sand could be obtained in this study.

5.1 Effect of Lime and Lime-Emulsion on Strength Parameters Cu and ϕ_u

Fig. 20 is plotted to show the effect of adding 3% lime on the strength parameters Cu and ϕ_u of silty sand. The results presented in this figure was obtained from the specimens cured in sealed plastic bags for 7 days. The values of Cu and ϕ_u for untreated silty sand are also shown in the figure.

It appears that both Cu and ϕ_u of silty sand are affected by the addition of 3% lime. The specimens of silty sand with 3% lime (S+3L) developed 11.0 lb/in^2 of cohesion intercept after 7 days of curing, and about one degree of ϕ_u was increased at the same time.

The development of cohesive strength of stabilized silty sand is believed to be mainly due to the pozzolanic reaction between lime and silty sand which results in cementing soil particles together. The increase in ϕ_u of silty sand with the presence of 3% lime is undoubtedly because of the agglomeration reaction. Through this process, the fine particles are allowed to form coarser grains and thus the value of ϕ_u is increased.

Fig. 21 compares the Mohr envelopes of S+3E, S+3L and S+3L+3E after curing for 7 days. It can be seen that the cohesion intercept exhibited by S+3L is slightly higher than that exhibited by S+3E. This points out that the effect of 3% lime on the cohesive strength of silty sand is greater than that of 3% emulsion. However, it is obvious from the figure that silty sand stabilized with 3% lime plus 3% emulsion (S+3L+3E) gives higher value of Cu than that with only 3% lime or 3% emulsion. This tends to indicate that the addition of emulsion to

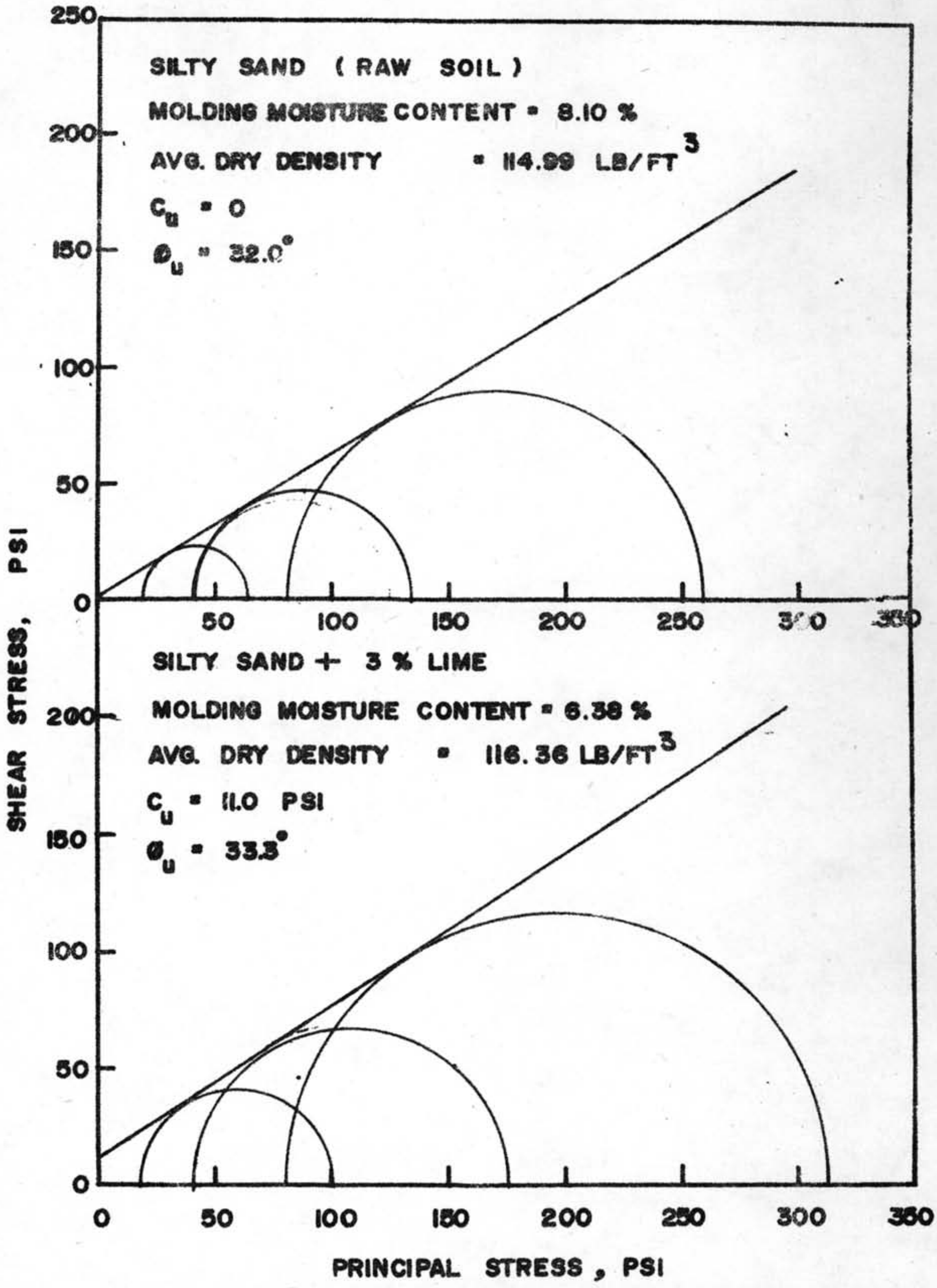

FIGURE 20. TYPICAL MOHR ENVELOPÉS OF RAW SOIL AND SOIL— EMULSION.

CURING TIME = 7 DAYS.

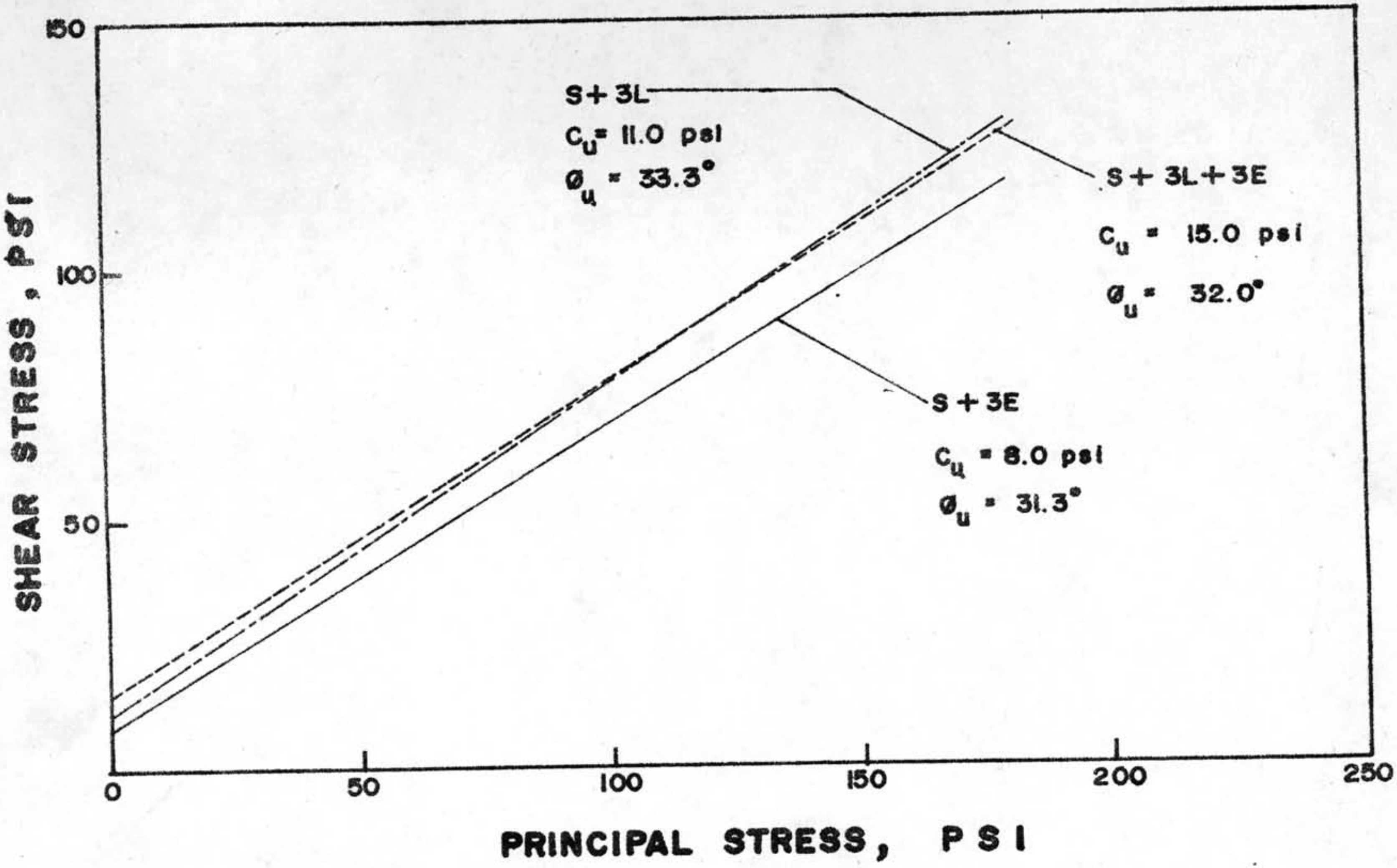

FIGURE 21. MOHR ENVELOPES OF SILTY SAND STABILIZED WITH LIME , EMULSION AND LIME — EMULSION.

CURING TIME = 7 DAYS

soil-lime mixture causes an increase in the cohesive strength. In other words, the cohesive strength of soil-emulsion can be improved by pretreating the raw soil with lime before adding emulsion.

Emulsion added to lime-treated silty sand appears to affect the parameter ϕ_u in the same manner as when it is added to untreated silty sand. Three percent emulsion causes ϕ_u of S+3L to decrease from 33.3° to 32.0°. This is undoubtedly due to the lubricating effect of emulsion. However, it can be seen that the value of ϕ_u of S+3L+3E is still higher than that of S+3E. This may lead to the conclusion that the presence of lime in soil-emulsion system not only improves the cohesive strength of soil-emulsion, but also increases the angle of shearing resistance.

5.2 Effect of Curing Time on Strength of Soil-Lime-Emulsion

The unconfined compressive strength exhibited by the moist specimens (cured in sealed plastic bags) of S+3E, S+3L and S+3L+3E are plotted against the curing time as shown in Fig. 22. After one day of curing, silty sand with 3% lime plus 3% emulsion shows higher strength than that with 3% lime or with 3% emulsion only. By comparing the one-day strength of soil-lime to that of soil-emulsion, it can be seen that with the same percentage of stabilizers used, soil-lime give higher strength than soil-emulsion.

With longer curing, the strength of the specimens continues to increase at different rate. The increase in strength of soil-lime-emulsion with increasing curing time appears to be faster than those of soil-lime and soil-emulsion. As mentioned in Art. 4.3 of

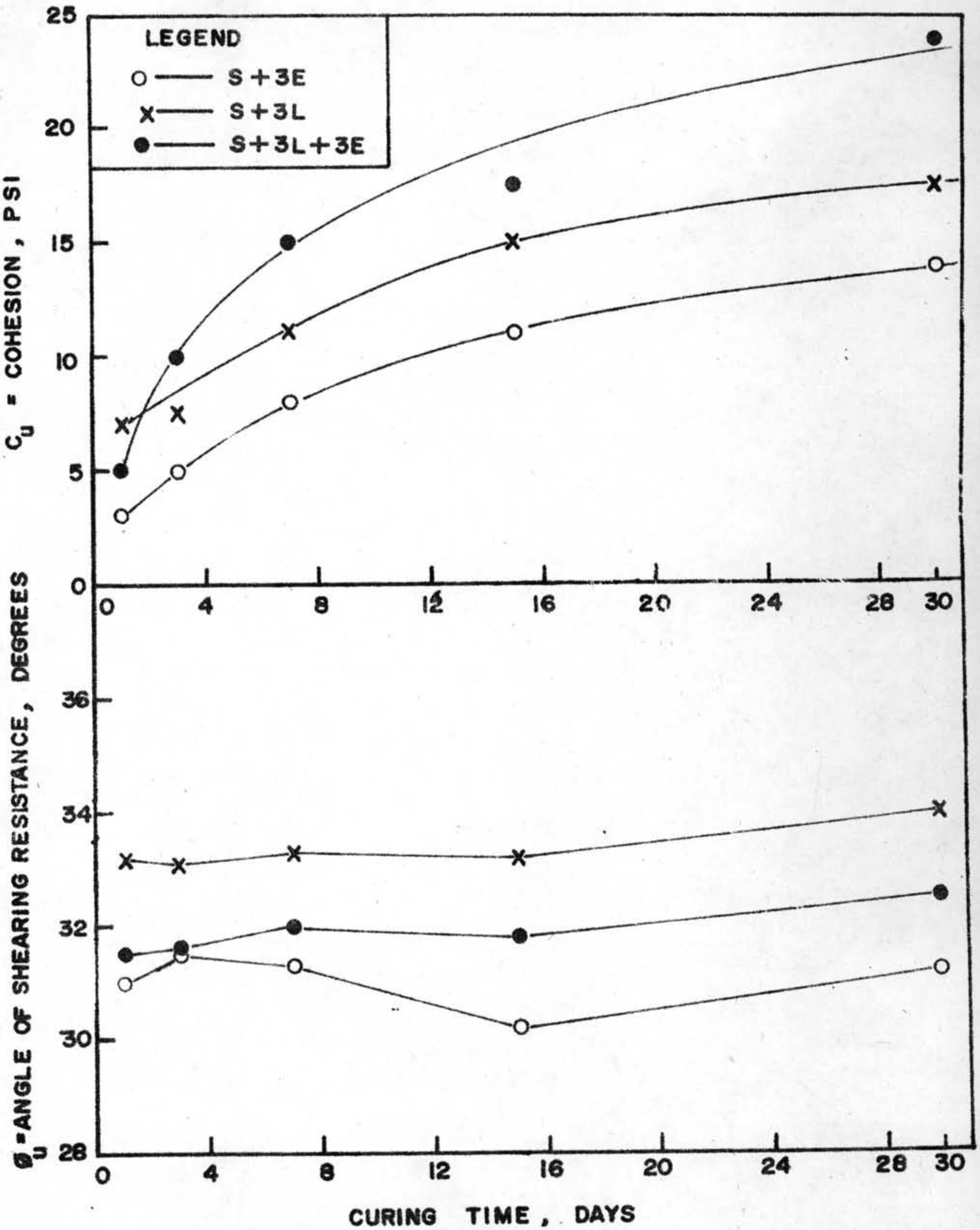

FIGURE 23. COHESION AND ANGLE OF SHEARING RESISTANCE VS. CURING TIME FOR SILTY SAND STABILIZED WITH EMULSION , LIME AND LIME — EMULSION .

this chapter, the strength development of soil-emulsion is in fact caused by the evaporation of moisture in the specimens. For soil-lime and also soil-lime-emulsion, the development of strength is partly due to the change in moisture content and partly due to the chemical reaction between lime and soil particles.

In soil-lime-emulsion system, when lime is added to silty sand, the chemical reaction will start immediately as soon as water is added. Agglomeration, flocculation and base exchange will gradually occur, allowing fine particles to form coarser grains. The emulsion added to soil-lime will then be distributed and partly coat those agglomerated coarser grains. Upon molding and compaction of the mix, the free void between soil grains is reduced and the dispersed emulsion particles are squeezed out into filaments and laminar, which occupy a rather large fraction of the void space. Therefore the strength of this mix in this stage comes partly from internal friction between agglomerated soils and partly from adhesion between agglomerated soil-lime resulted from added emulsion. Pozzolanic reaction, which takes place rather slowly in the mix, is the main factor allowing the specimen to develop strength over long period of time. Asphalt from the emulsion in the mix, which partly coats the agglomerated soil, will help to eliminate the undesirable carbonation reaction. For these reasons, addition of 3% emulsion to soil-lime in this study results in increasing the strength of soil-lime.

Fig. 23 is plotted to show the effect of curing time on the parameters Cu and ϕ_u of soil-emulsion, soil-lime and soil-lime-emulsion. The specimens of each mix appear to develop cohesive strength in a manner similar to the development of unconfined compressive strength (Fig.22).

Although higher value of ϕ_u could be obtained by adding lime, there appears to be a tendency that ϕ_u of soil-lime and soil-lime-emulsion as well as of soil-emulsion (Fig.16) is unaffected by the curing time. After curing for one day, 3% lime causes ϕ_u of silty sand to increase by about one degree. With longer curing time, the value of parameter ϕ_u of S+3L appears to be approximately the same. This indicates that the agglomeration reaction, which produces the agglomerated silty sand, takes place and completes within only one day. For soil-lime-emulsion (S+3L+3E), the result shows the same behavior as for soil-lime (S+3L). Therefore it can be concluded that the angle of shearing resistance of soil-lime and also soil-lime-emulsion are independent of the curing time. In other words, the strength increase of soil-lime or soil-lime-emulsion with increasing curing time is mainly due to the development of cohesive strength.

5.3 Effect of Curing Type on Strength of Soil-lime-Emulsion

Figure 24 illustrates the effect of curing type on the unconfined compressive strength of soil-lime-emulsion. A plot of moisture content loss versus curing time for each type of curing is also included in the figure. The results show that with the same curing time, the air-dried specimens of silty sand with 3% lime and 3% emulsion developed higher strength than the moist specimens.

The one-day strength exhibited by the air-dried specimens is about three times of that exhibited by the moist specimens. With longer curing time, the strength of air-dried specimens was found to increase rapidly and reach a maximum value within 7 days of curing. Large increase in strength of these specimens is believed to be due to the evaporation of moisture in the specimens which took place rapidly during the first 7 days. The rapid rate of moixture evaporation will then result in rapid hardening of cementitious gel produced by the pozzolanic reaction. No more strength developed after 7 days indicates that there was no further pozzolanic reaction occuring after that time.

For moist specimens, although some amount of moisture could be evaporated during the curing process, the major portion of moisture was still retained in the specimens and the pozzolanic reaction could take place gradually throughout the entire curing period of this investigation. For this reason, increasing curing time will result in continuous development of strength of the moist specimens.

When tested by the method of undrained triaxial test, the results as shown in Fig. 25 indicate that the curing type has significant effect on the cohesion intercept (cohesive strength) of soil-lime-emulsion. By air-dried curing, it was found that the specimens developed cohesive strength rapidly at the beginning of curing time. The one-day value of Cu exhibited by air-dried specimens is about three times of that exhibited by the moist specimens. With longer curing, the air-dried specimens increased cohesive strength at a faster rate than the moist specimens. This phenomemon can be explained by the same reason as used for explaining the effect of curing type on the development of unconfined compressive strength of soil-lime-emulsion. For each type of curing, it can be

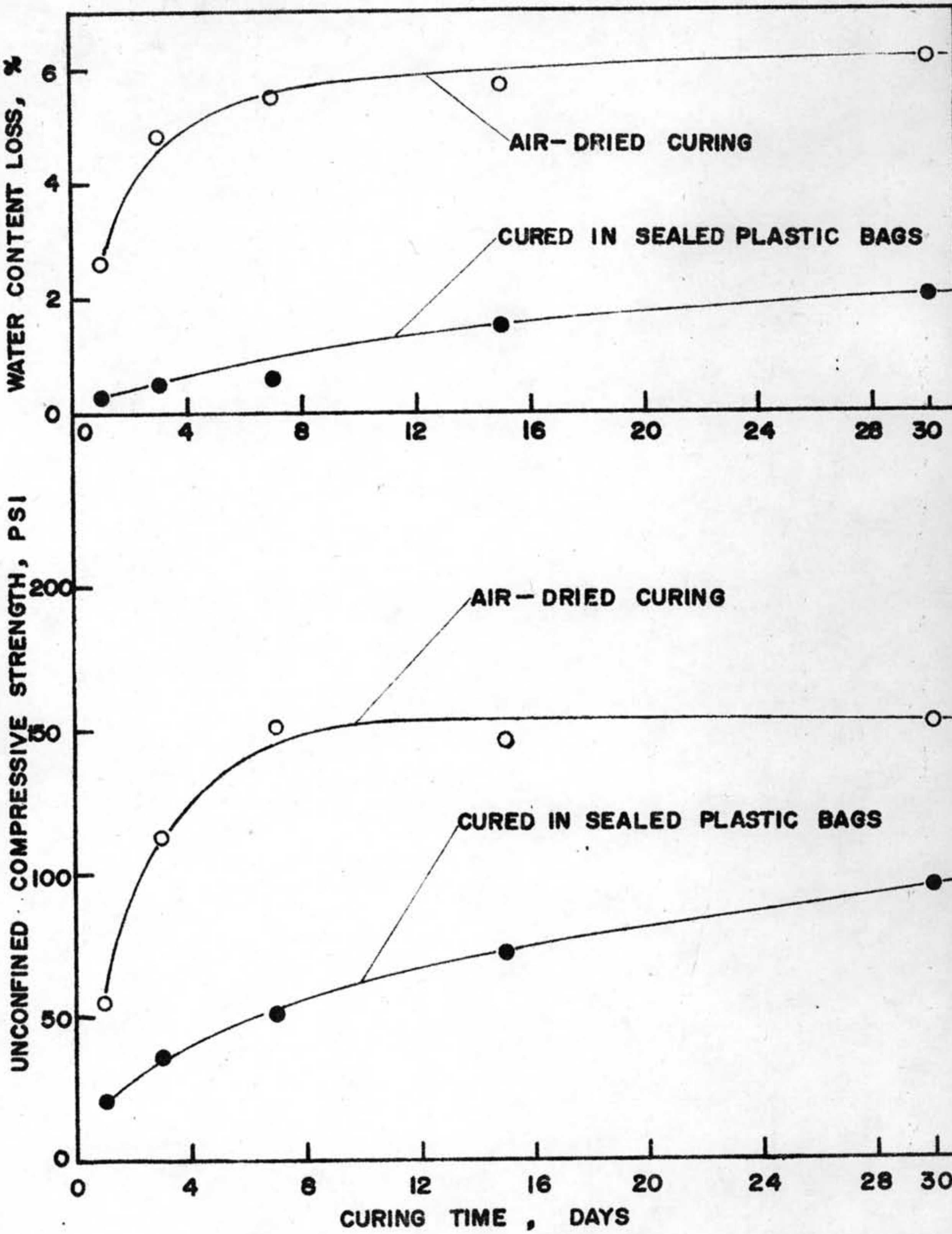

FIGURE 24. EFFECT OF CURING TYPES ON UNCONFINED COMPRESSIVE STRENGTH OF SOIL-LIME-EMULSION.

(SILTY SAND WITH 3 % LIME AND 3 % EMULSION)

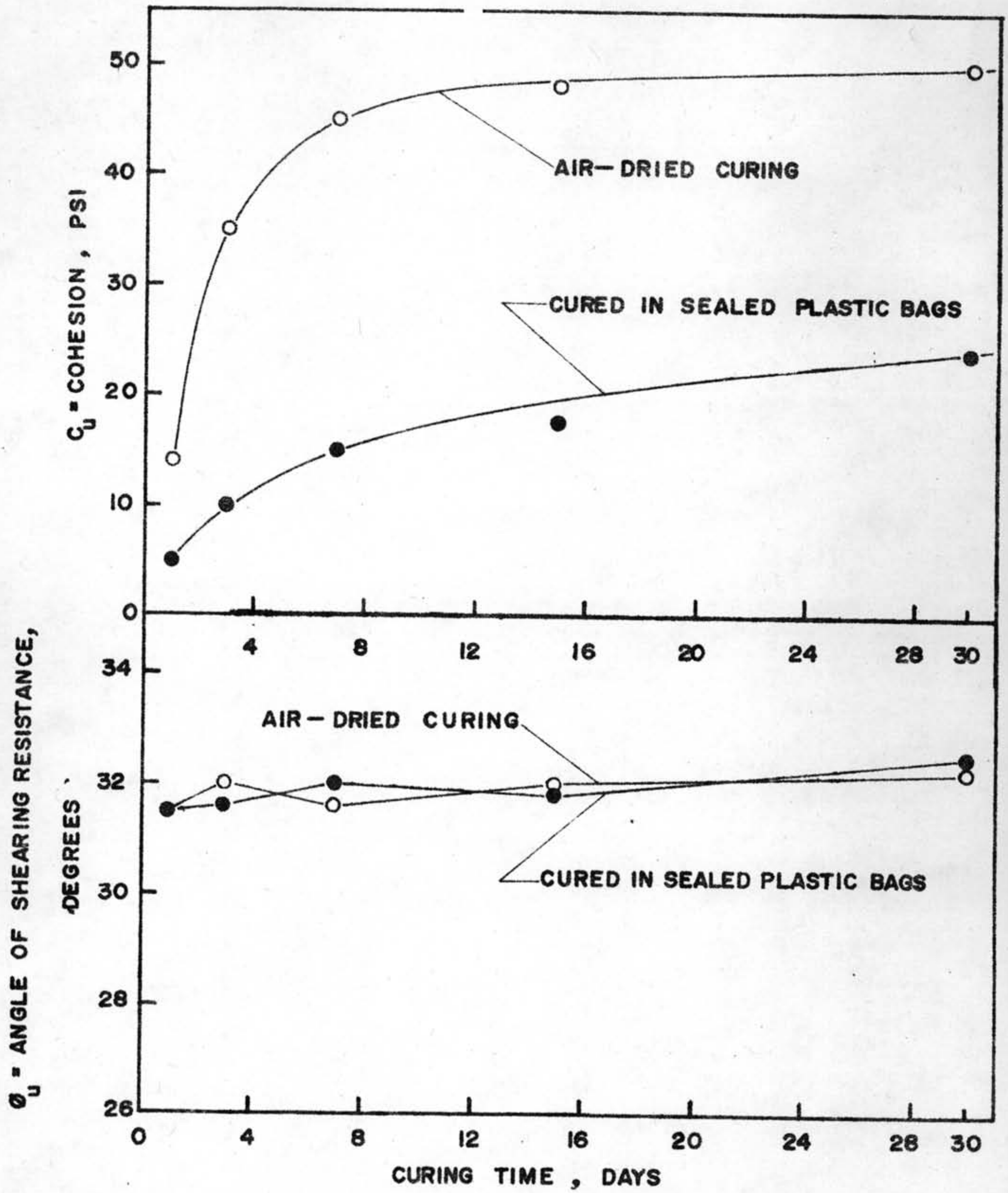

FIGURE 25. EFFECT OF CURING TYPES ON UNDRAINED STRENGTH OF SOIL—LIME—EMULSION.

(SILTY SAND WITH 3 % LIME 3 % EMULSION) seen that the specimens of S+3L+3E developed the value of Cu and the unconfined compressive strength in the same manner.

As has already been discussed in the previous section, the agglomeration which causes ϕ_u of soil-lime-emulsion to be increased was found to completely take place within one day of curing, and the value of ϕ_u of moist specimens is not affected by increasing curing time. For air-dried specimens, the results obtained also show the similar trend. The one-day value of ϕ_u of air-dried specimens was found to be the same as that of moist specimens; and with longer curing time, it appears that the angle of shearing resistance of air-dried specimens is also independent of curing time. The same one-day value of ϕ_u of air-dried specimens and of moist specimens indicates that the curing types have no effect on the agglomeration reaction. In other words, the different moisture content of the air-dried specimens and the moist specimens, after one-day curing, does not affect the process of agglomeration.

Therefore it can be concluded that the angle of shearing resistance of soil-lime-emulsion is independent of curing type. In addition, the cohesion intercept (cohesive strength) as well as the unconfined compressive strength are greatly affected by the curing type.

6. Cement-Emulsion Stabilization

In this study, three percent cement was used in conjunction with three percent emulsion for stabilizing silty sand and beach sand. The methods for preparing, curing, and testing specimens as well as the molding moisture content were also the same as those used for the specimens of soil-emulsion and soil-lime-emulsion.

In order to clearify the effect of cement on the strength properties of sandy soils, three percent was used to stabilize silty sand and beach sand. Unfortunately, it was found that the specimens of beach sand with 3% cement (B+3C) could not be molded. The strength characteristic of soil-cement was therefore evaluated from only the test results of silty sand with 3% cement (S+3C).

For the purpose of studying the effect of curing type, another set of specimens of silty sand with 3% cement and 3% emulsion (S+3C+3E) were prepared and cured by the air-dried method. The results obtained from the air-dried specimens were then compared to those from the moist specimens (cured in sealed plastic bags).

All of the detailed test results of this type of stabilization are summarized in Appendices B and C.

6.1 Effect of Cement and Cement-Emulsion on Strength Parameters Cu and ϕ_u

Data presented in Fig. 26 illustrates the effect of 3% cement on Cu and ϕ_u of silty sand. It can be seen that cement-treated silty sand, after 7 days of curing, developed values of cohesion and internal triction that are markedly higher than those for untreated silty sand. The large increase in angle of shearing resistance, ϕ_u, of silty sand when 3% cement is added reflects the large increase in effective maximum particle size and change in gradation which take place.

The strength parameters Cu and ϕ_u for soil-emulsion, soil-cement and soil-cement-emulsion are compared in Figures 27 and 28. It is obvious from the figure that when added to the mixture of silty sand and emulsion, the effect of 3% cement on the values of Cu and ϕ_u is smaller than it is added to silty sand alone. This is in agreement with the fact that with the presence of emulsion, the soil particles will be partially coated with asphalt and thus some part of cementing action produced by hydration of cement will be prevented.

The higher values of Cu and ϕ_u of S+3C+3E than of S+3E as well as the higher values of Cu and ϕ_u of B+3C+4E than of B+4E indicate that the strength properties of soil-emulsion could be effectively improved by the addition of 3% cement. Adding 3% emulsion to silty sand results in providing some cohesive strength and in reducing ϕ_u by about one degree. The application of 3% cement to mixture of silty sand and 3% emulsion causes the cohesion intercept to increase from 8.0 psi to 47.0 psi and also causes ϕ_u to increase from 31.3° to 35.0°. This points out that stabilization by using emulsion in conjunction with cement not only provides the waterproofing and cementing properties but also increases the angle of shearing resistances.

The decreases in the values of Cu and ϕ_u of soil-cement-emulsion due to increasing emulsion content (from 3% to 4% by this case) reflect the effect of additional asphalt in preventing the cementing action. This tends to be true for both silty sand and beach sand.

For comparison purposes, the 7 days values of Cu and ϕ_u

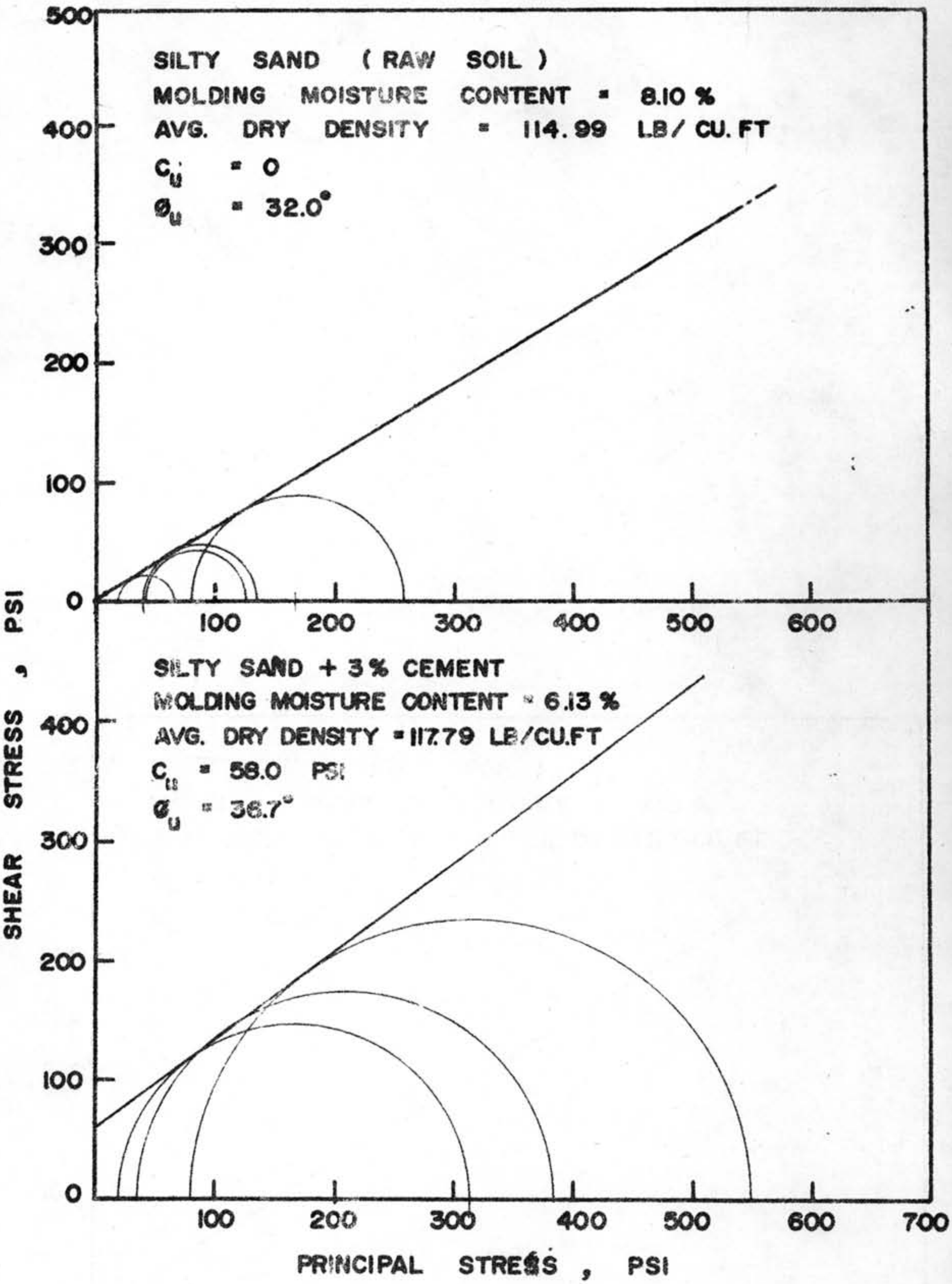

FIGURE 26. TYPICAL MOHR CIRCLES OF RAW SOIL AND SOIL — CEMENT

CURING TIME = 7 DAYS

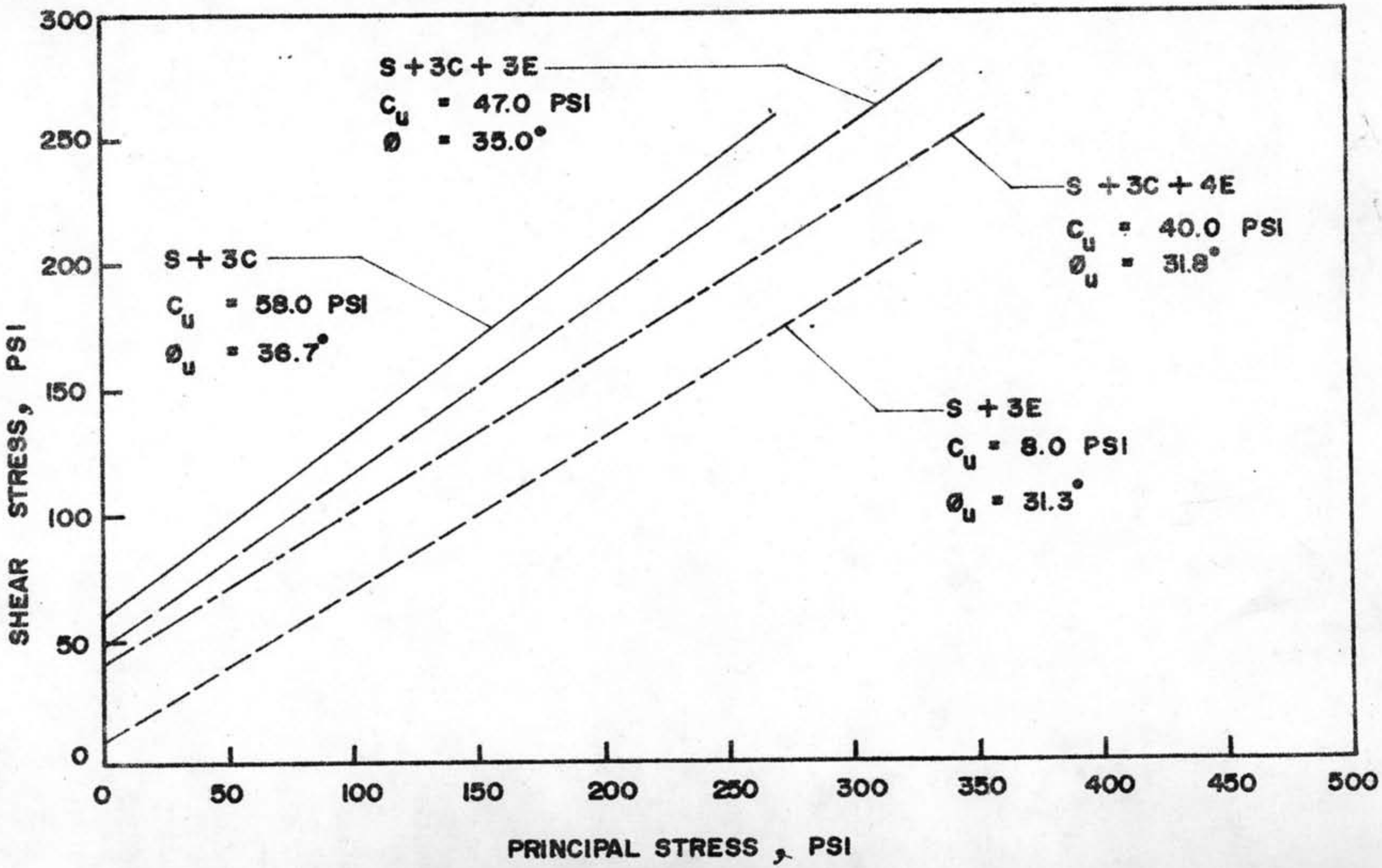

FIGURE 27. MOHR ENVELOPES OF SILTY SAND STABILIZED WITH EMULSION, CEMENT AND CEMENT — EMULSION

CURING TIME = 7 DAYS

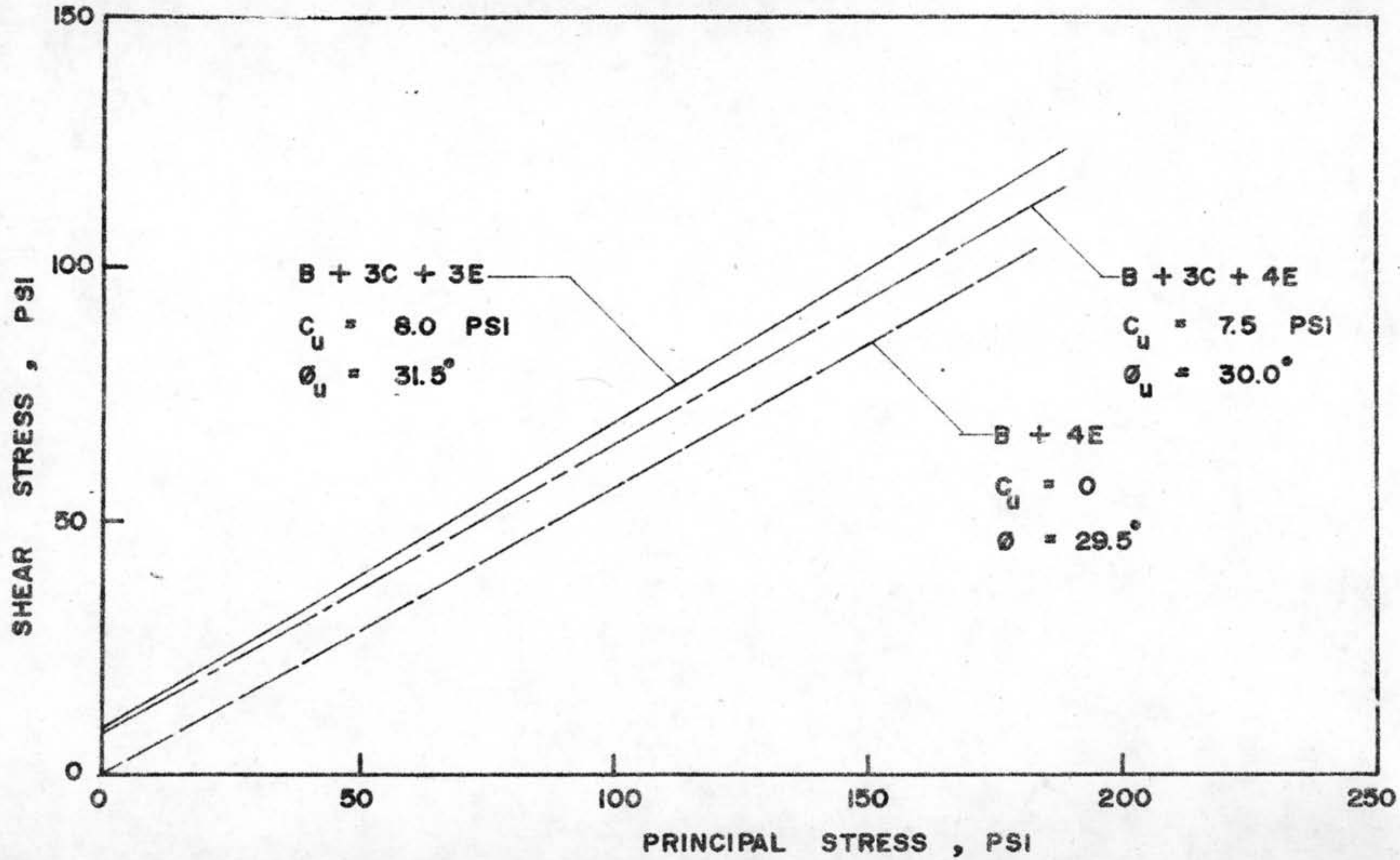

FIGURE 28. MOHR ENVELOPES OF BEACH SAND STABILIZED WITH EMULSION AND CEMENT – EMULSION.

CURING TIME = 7 DAYS

Table 8 - Comparison of 7 - day values of Strength Parameters Cu and ϕ_u for Various types of Stabilization

Types of Mixes	Cu (psi)	ϕ_u (deg)
Untreated Silty sand	0	32.0
S+3E	8.0	31.3
S+4E	8.0	31.0
S+5E	12.5	29.0
S+3L	11.0	33.3
S+3L+3E	15.0	32.0
S+3C	58.0	36.7
S+3C+3E	47.0	35.0
S+3C+4E	40.0	31.8
B+4E	0	29.5
B+5E	2.5	29.0
B+3C+3E	8.0	31.5
B+3C+4E	7.5	30.0

* Obtained from the specimens which had been cured in sealed plastic bags for 7 days

of silty sand and beach sand stabilized with various types of stabilizers are summarized in Table 8. It is obvious from the table that with the same percentage of stabilizers and the same curing time, soil-cement develops much greater values of cohesion and internal friction than soil-lime and soil-emulsion. Furthermore, the use of 3% cement as an additive for soil-emulsion appears to be much more effective than the use of 3% lime.

By comparing the results of stabilized silty sand and stabilized beach sand, it can be seen that the cohesion intercept exhibited by S+3C+3E is much greater than that exhibited by B+3C+3E. This can be explained by the fact that the reaction between cement and soil particles is more effective in silty sand than in beach sand.

6.2 Effect of Curing Time on Strength of Soil-Cement-Emulsion

A plot of unconfined compressive strength versus curing time for silty sand stabilized with 3% cement and 3% emulsion (S+3C+3E) is given in Fig. 29. Also included in the figure are data for silty sand with 3% emulsion (S+3E) and silty sand with 3% cement (S+3C). All of the results presented in the figure were obtained from those specimens having been cured in sealed plastic bags.

As discussed in Art. 4.2 and 4.3 of this chapter, the moisture in the specimens would be somewhat evaporated when this type of curing was employed. In the case of soil-emulsion, the increase in strength with increasing curing time is said to be mainly due to the loss of moisture content in the specimens. For soil-cement and also soil-cement-emulsion, hydration of cement is another factor which causes an increase in strength with increasing curing time.

As shown in Fig. 29, the rate of strength development of S+3C and S+3C+3E is much faster than that of S+3E. This tends to indicate that the effect of hydration of cement is much pronounced when compared to that effect due to the loss of moisture content in the specimens.

It has long been recognized that the strength of soil-cement derives from (a) the strength of hydration products of the cement particles and (b) the strength of the secondary reaction products which are formed between the released lime and the soil. The cement hydration usually coours in a relatively short period of time, and the formation of secondary cementitious materials due to the pozzolanic reactions is much slower (20). This points out that the portion of strength of soil-cement developed in the early curing time is mainly due to the strength of hydration products of cement, consequently, the increase in strength which takes place gradually over the long period of curing is due to the pozzolanic reaction. In general, with a proper amount of cement, the major portion of strength in cement-treated soil is developed at the beginning of curing time and then increases at a decreasing rate with longer curing. The data obtained in this study for silty sand with 3% cement also shows the similar trend.

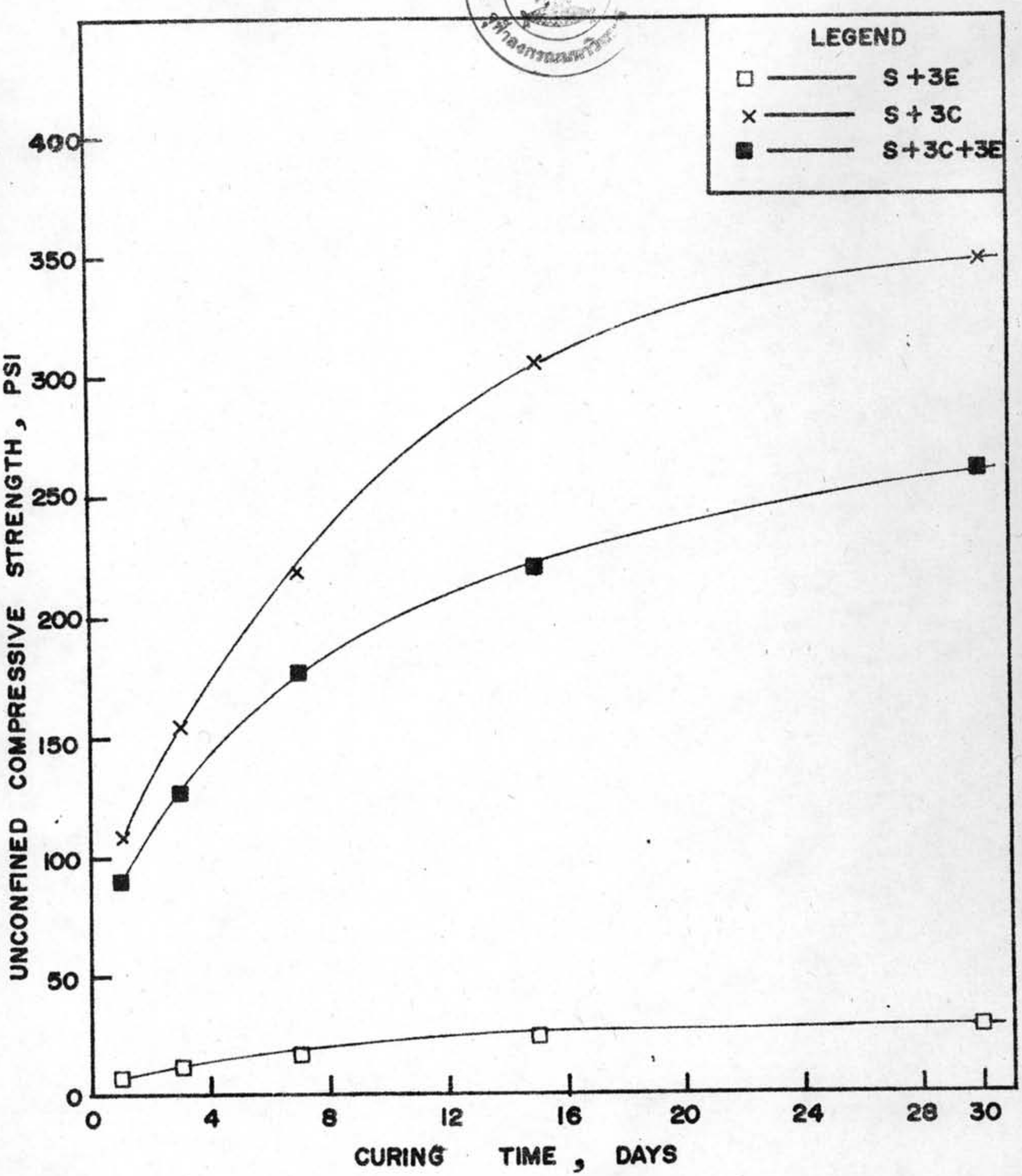

FIGURE 29. UNCONFINED COMPRESSIVE STRENGTH VS. CURING TIME FOR SILTY SAND STABILIZED WITH EMULSION, CEMENT AND CEMENT – EMULSION

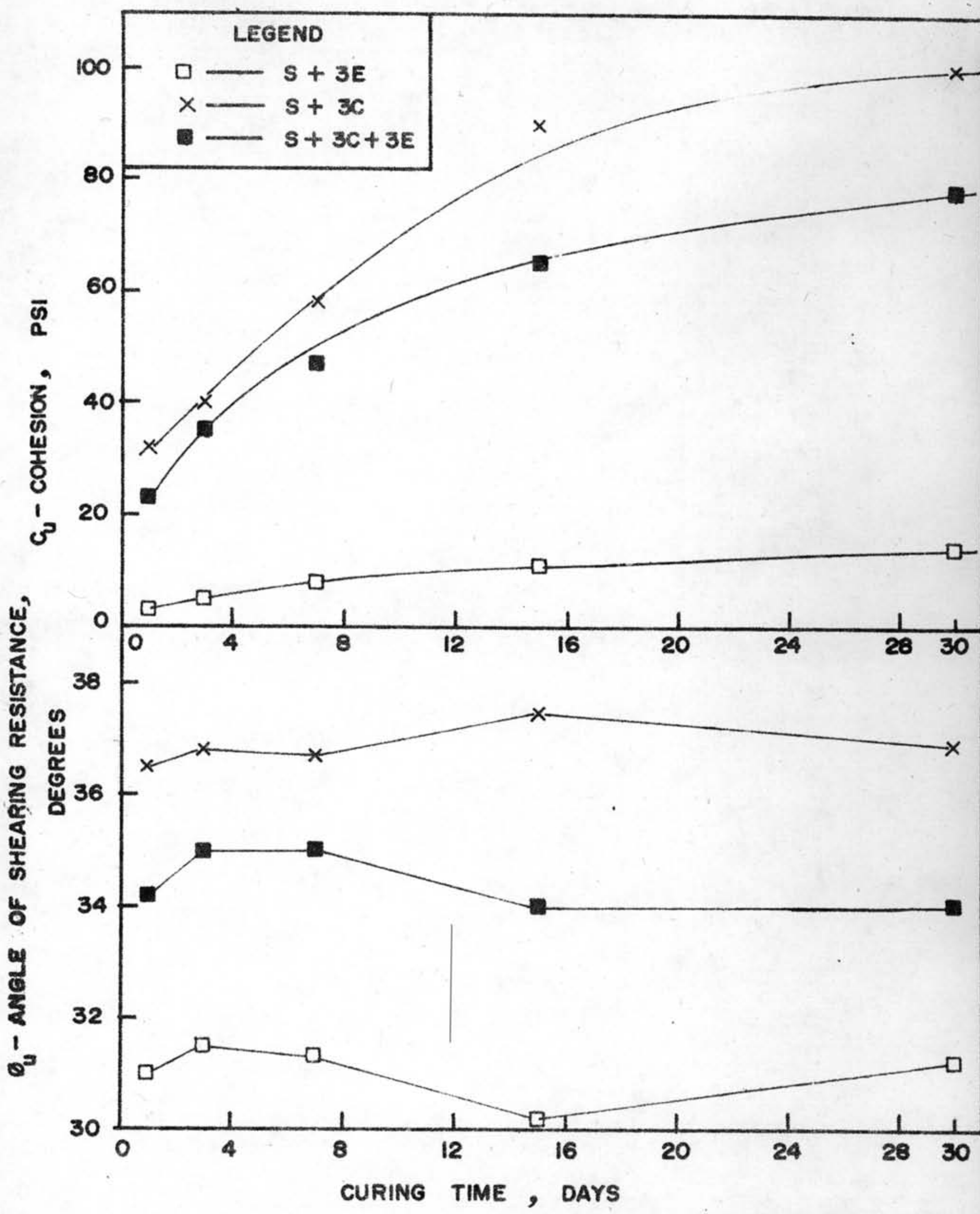

FIGURE 30. COHESION AND ANGLE OF SHEARING RESISTANCE VS. CURING TIME FOR SILTY SAND STABILIZED WITH EMULSION, CEMENT AND CEMENT-EMULSION

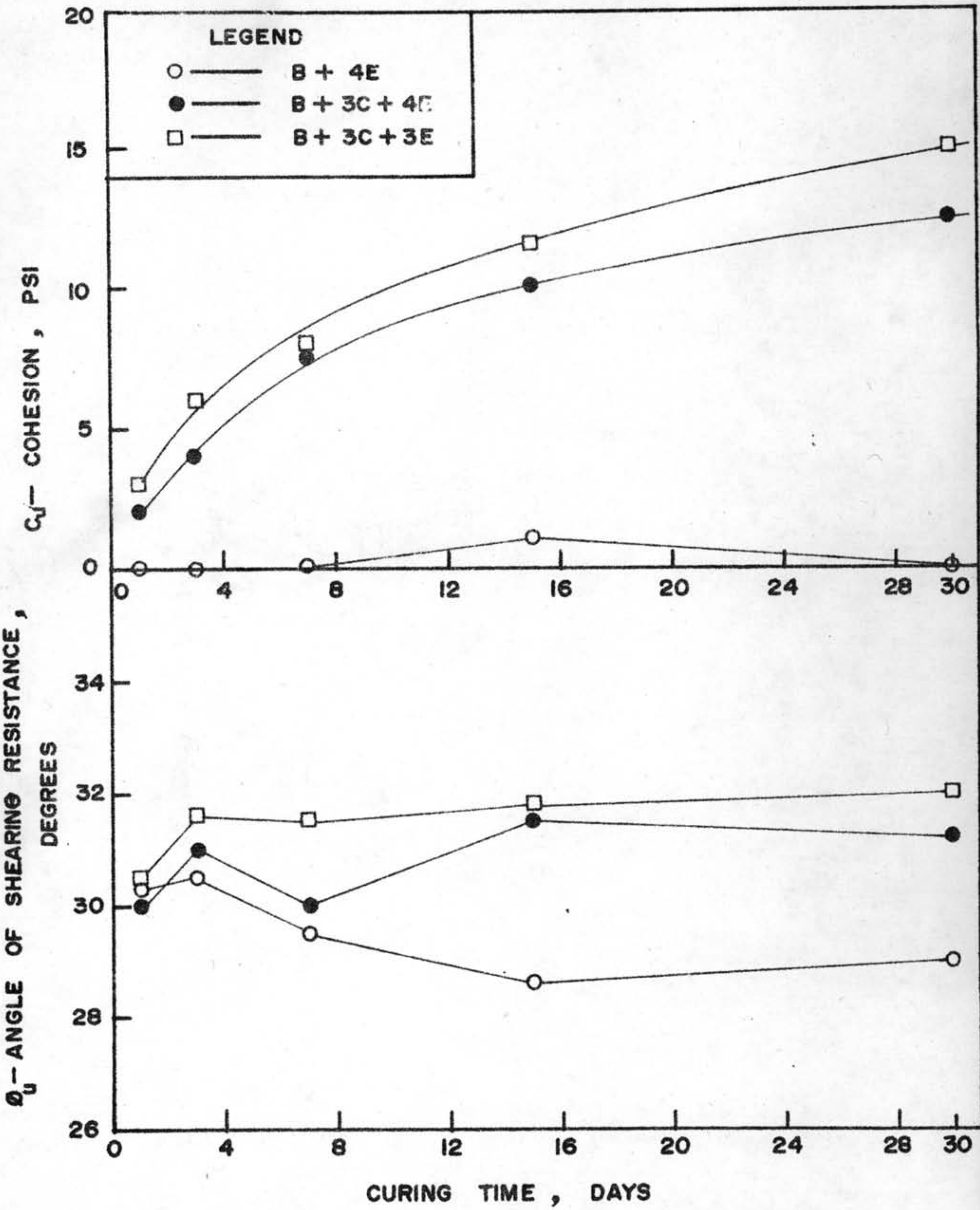

FIGURE 31. COHESION AND ANGLE OF SHEARING RESISTANCE VS. CURING TIME FOR BEACH SAND STABILIZED WITH EMULSION AND CEMENT — EMULSION

It is obvious (from Fig. 29) that the rate of strength increase of S+3C+3E is slower than S+3C. This is undoubtedly due to the fact that with the presence of emulsion, some part of cementing action produced by cement hydration and also by pozzolanic reaction is prevented by asphalt.

The effect of curing time on the strength of soil-cement and soil-cement-emulsion can be illustrated separately in terms of cohesion and internal friction as shown in Figures 30 and 31. It can be clearly seen that for both silty sand and beach sand, the curing time has marked influence on the development of cohesive strength of soil-cement-emulsion. By comparing between soil-cement-emulsion and soil-cement-emulsion, the result from Fig. 30 shows that silty sand with 3% cement develops cohesive strength at a faster rate than with 3% emulsion. This indicates that in soil-cement-emulsion system, the presence of emulsion is deleterious to the development of cohesive strength. For beach sand, the cohesive strength developed by 4% emulsion, if any, was found to be very little and not affected by the curing time. But when 3% cement was added, small value of cohesion intercept could be measured after curing for one day and then became larger with longer curing time.

Although addition of cement into soil or soil-emulsion results in increasing the angle of shearing resistance, there appears to be a tendency that very little or no change in the value of ϕ_u takes place after one-day curing. For each type of mix for both silty sand and beach sand, the values measured at age one day, 3 days, or at any longer curing periods, were found to be nearly the same. This indicates that the internal friction of soil-cement or soil-cement emulsion is already changed within only one day after the addition of cement. It other words, the curing time longer than one day does not affect the angle of shearing resistance of soil-cement and soil-cement-emulsion.

6.3 Effect of Curing Type on Strength of Soil-Cement-Emulsion

Figs. 32 and 33 show the effect of curing type on the unconfined compressive strength and the values of parameters Cu and ϕ_u of silty sand stabilized with 3% cement and 3% emulsion. When cured by air-dried method, the specimens appear to develop strength (unconfined compressive strength) in a manner different from those specimens cured in sealed plastic bags. After curing for one day, the strength exhibited by air-dried specimens is somewhat greater than that exhibited by the moist specimens. With longer curing time, the air-dried specimens developed strength rapidly during the first 7 days.

After 7 days of curing, no further development of strength of the air-dried specimens took place, whereas the strength of the moist specimens continued to increase with increasing time and became higher than that of the air-dried specimens when measured at age 30 days. No more strength developed by the air-dried specimens after 7 days of curing reflects the lack of water in the specimens to permit the hydration of cement and also

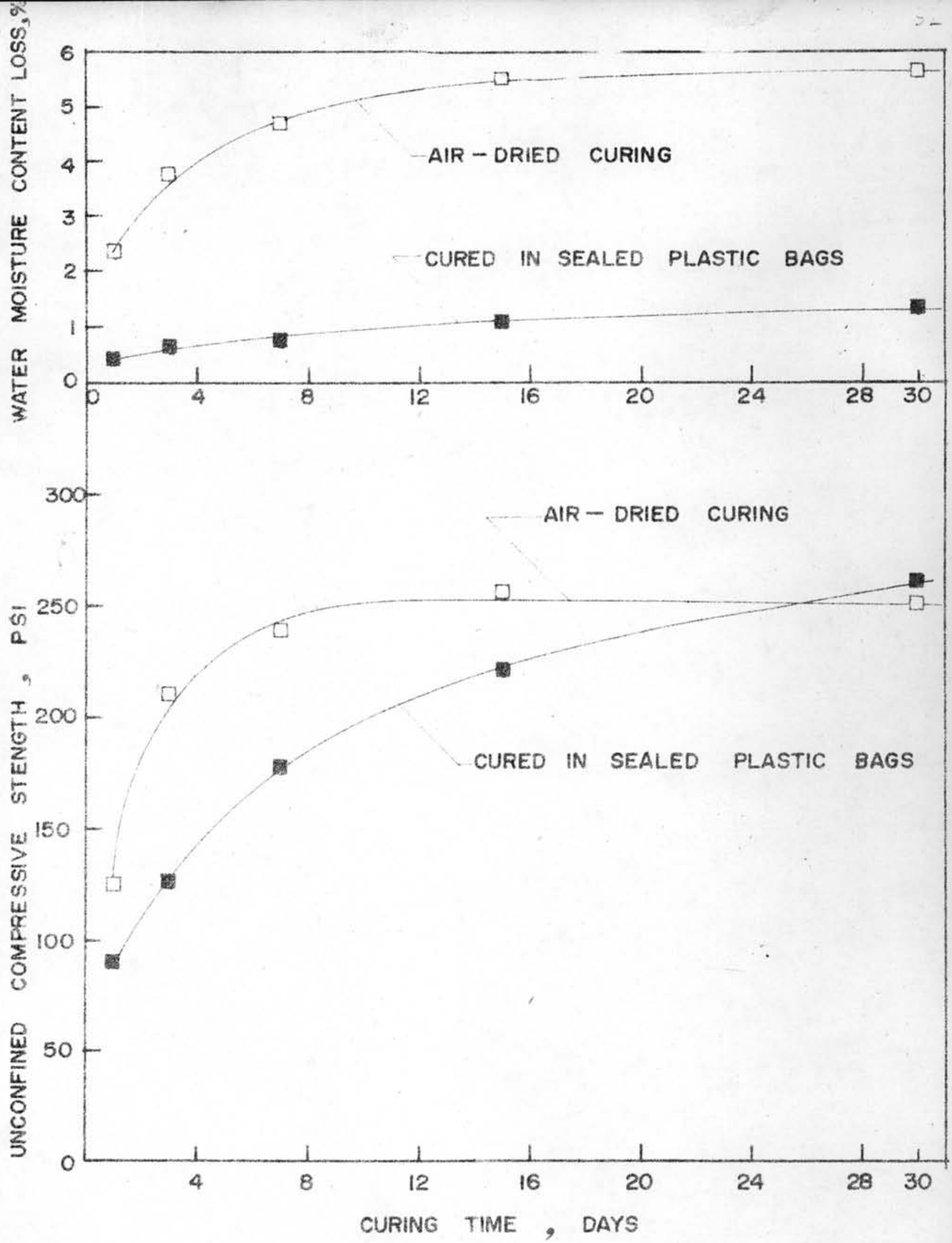

FIGURE 32. EFFECT OF CURING TYPES ON UNCONFINED COMPRESSIVE STRENGTH OF SOIL – CEMENT – EMULSION

(SILTY SAND WITH 3 % CEMENT AND 3 % EMULSION)

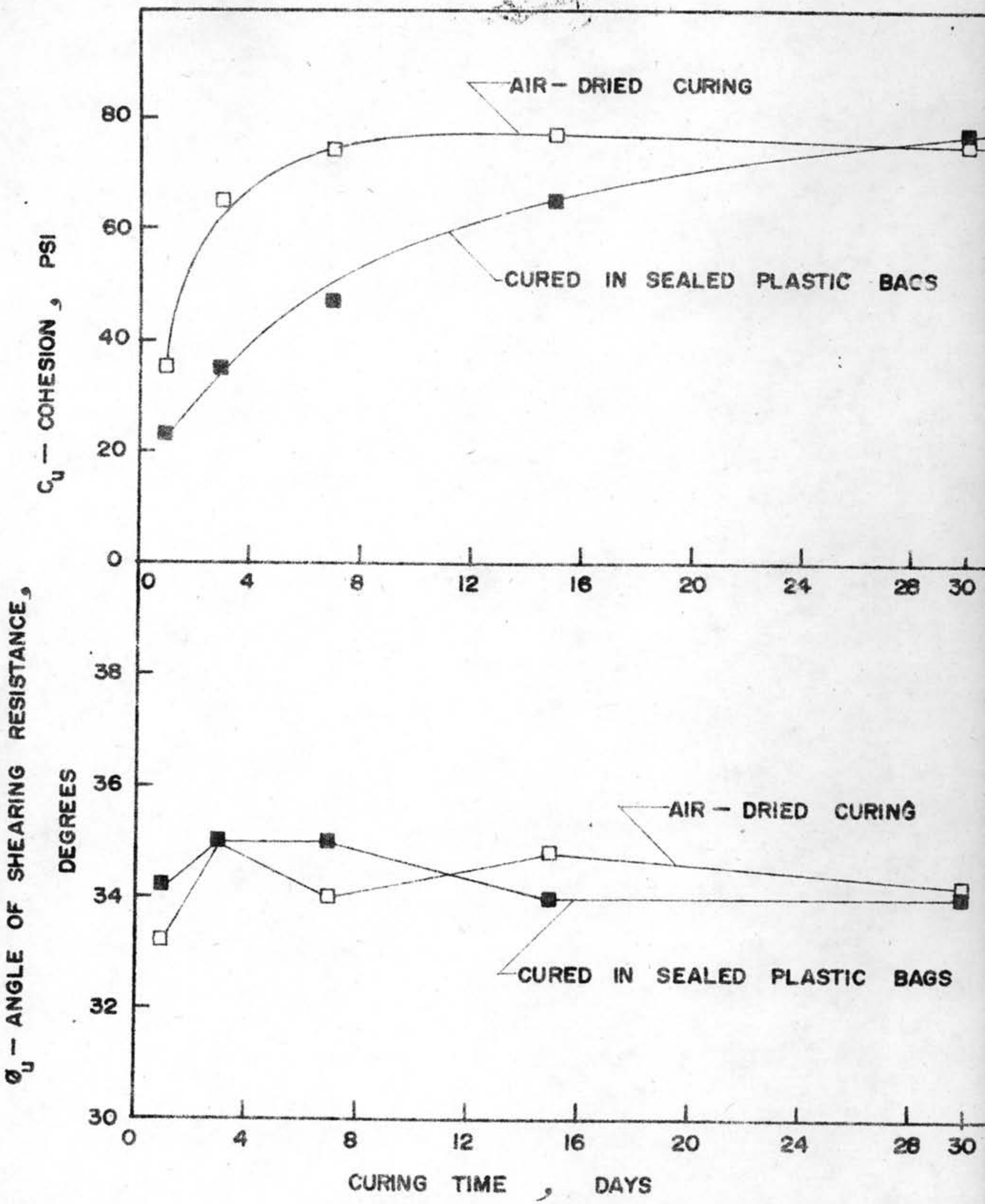

FIGURE 33. EFFECT OF CURING TYPES ON UNDRAINED STRENGTH OF SOIL–CEMENT–EMULSION

(SILTY SAND WITH 3 % CEMENT & 3 % EMULSION) the pozzolanic reaction (between released lime and soil particles).

By comparing the results in Fig 32 with the results in Fig. 24 (for soil-lime-emulsion), it can be seen that with either type of curing, the strength development of soil-cement-emulsion is quite similar to that of soil-lime-emulsion. Furthermore, it likely seems that the effect of curing types is more pronounced for soil-lime-emulsion than for soil-cement-emulsion. The air-dried specimens of soil-lime-emulsion developed much higher strength than the moist specimens, whereas for soil-cement-emulsion, the air-dried strength is somewhat different from the strength exhibited by the moist specimens with the same curing time. However, with the same percentage of stabilizers and the same curing time and curing type, soil-cement-emulsion gives much higher strength than soil-lime-emulsion.

As a result from this comparison, it should be suggested here that the air-dried curing type should be reasonably employed for curing the specimens of soil-lime-emulsion, since with this curing type, a relatively high value of strength could be obtained. For soil-cement-emulsion, the curing type with prevention of moisture evaporation appears to give better results than the air-dried curing type.

As shown in Fig. 33, the effect of curing types is illustrated separately in terms of Cu and ϕ_u. It can be seen that the curing type has important effect on the development of cohesion intercept, Cu, of soil-cement-emulsion. The different rate of moisture evaporation tends to cause the cohesive strength to be increased at different rate.

For each type of curing, the development of cohesive strength of S+3C+3E was found to be in a similar manner as that of the unconfined compressive strength (See Fig.32). In the case of internal friction or the angle of shearing resistance, although the values of ϕ_u obtained from the air-dried specimens and the moist specimens are somewhat different, it is quite clear that such difference is not resulted from the curing type. This will lead to the conclusion that the the angle of shearing resistance of soil-cement-emulsion is independent of curing type. In other words, the different condition in evaporation of the moisture in the specimens has no effect on the angle of shearing resistance of soil-cement-emulsion as well as of soil-emulsion and soil-lime-emulsion. Furthermore, the cohesive strength (cohesion intercept-Cu) as well as the unconfined compressive strength of soil-cement-emulsion is markedly affected by the curing type.