4 Results: California Bearing Ratio (CBR)

CBR-value is used as an index of soil strength and bearing capacity. This value is broadly used and applied in design of the base and the sub-base material for pavement. Lime- and fly ash–stabilized soils are often used for the construction of these pavement layers and also for embankments. CBR-value is a familiar indicator test used to evaluate the strength of soils for these applications (Nicholson et al., 1994). CBR-test was conducted to characterize the strength and the bearing capacity of the three studied soils and their mixtures with lime, fly ash, and lime/fly ash. The test procedures and the preparation of the specimens were achieved according to the procedures in chapter 2.4.2 and 2.5, respectively.

4.1 CBR of untreated compacted soils

CBR-values of the three tested soils, compacted at optimum water content, are given in Tables 2.8, 3.1, 3.2, and 3.3 (see chapter 2.3.4 and 3). All the specimens were prepared using a standard proctor test. Untreated compacted soil specimens (without chemical additives) of tertiary clay, organic silt, and weathered soil, compacted at optimum water content, had CBR-values of 4.6, 3.2, and 5.4%, respectively. CBR-values of untreated compacted soils need to be interpreted in the context of the general relationship between the CBR-values and the consistency (quality) of the soils used in pavement applications (Bowles, 1992). CBR-values ranging from 3 to 7% are considered as a poor to fair consistency. This means that the untreated compacted-tertiary clay, -weathered soil, and -organic silt belong to poor to fair consistency resulting from the compaction process at the optimum water content and without chemical additives “lime & fly ash” (see chapter 2.4.2 and Table 3.4).

4.2 CBR of treated stabilized soils

CBR-values of soil-lime, soil-fly ash, and soil-lime/fly ash mixtures prepared at optimum water content are given in Tables 3.1, 3.2, and 3.3 (see Appendixes 16, 17, & 18). CBR-value was measured after 7 days curing for the three studied soils.

Soil-lime mixtures of the three tested soils were prepared at the optimum lime content, 2%, and 4% above the optimum lime content (compacted at optimum water content) and cured for 7 days (see chapter 2.5.1). CBR-values are shown in Tables 3.1, 3.2, & 3.3 and in Figures 4.1 a & 4.2.

Soil-fly ash mixtures were prepared at 8, 12, 16, 20, and 25% fly ash for both the tertiary clay and the organic silt and at 8, 12, 16, 20, 25, and 35% fly ash for the weathered soil.
All the mixtures were compacted at optimum water content (two hours delay after the mixing) and cured for 7 days (see chapter 2.5.2).

Soil-fly ash mixtures of tertiary clay, organic silt, and weathered soil were prepared at the optimum fly ash content of 16, 20, and 35%, respectively (at optimum water content) and cured for 7, 28, 56, and 180 days to estimate the influence of curing time on the CBR-value and on the fly ash-stabilization process. The values of CBR are illustrated in Tables 3.1, 3.2, & 3.3 and in Figures 4.1 b & 4.2.

Soil-lime/fly ash mixtures were prepared at the optimum lime/fly ash contents, after pH-test, of (2.5%L/8%F), (2%L/12%F), and (3%L/20%F) for tertiary clay, organic silt, and weathered soil, respectively. Other mixtures were prepared at the optimum fly ash content with different lime percentages to evaluate the effect of the increase in the lime and the lime/fly ash ratio on the lime/fly ash-stabilization process (see chapter 2.5.3). All the mixtures were compacted at the optimum water content and cured for 7 days.

Soil-lime/fly ash mixtures of tertiary clay (2.5%L/16%F), organic silt (2%L/20%F), and weathered soil (3%L/35%F) were prepared at the optimum fly ash contents with small percentage of lime and at optimum water content (see chapter 2.5.3). The mixtures were cured for 7, 28, 56, and 180 days to evaluate the effect of the long-term curing on the CBR-value and on the lime/fly ash-stabilization process. CBR-values are illustrated in Tables 3.1, 3.2, & 3.3 and in Figures 4.1 c, 4.2, 4.3, & 4.4 (see Appendixes 16, 17, & 18).

4.2.1 General effect of lime-, fly ash- and lime/fly ash-stabilization process

The general effect of lime-, fly ash- and lime/fly ash-stabilization process on the three studied soils is illustrated in Figure 4.1 a, b, and c, respectively. The addition of the optimum lime content led to an increase in the CBR-values for the three tested soils. The lime-tertiary clay mixtures have the highest CBR-values, whereas the lime-weathered soil mixtures have the lowest values. The reactivity of the tertiary clay with lime is stronger than the reactivity of both the weathered soil and the organic silt. The CBR-values of lime-tertiary clay mixtures increased slightly with increasing lime content (2 and 4% above the optimum lime content). The reactivity of both the organic silt and the weathered soil with lime is weak, according to the reactivity test (see chapter 2.5.1). The lime-organic silt mixtures have CBR-values relatively higher than the CBR-values of lime-weathered soil mixtures. CBR-values of both lime stabilized-organic silt and -weathered soil increased with increasing lime content (2% above the optimum lime content) and decreased slightly with continual increase in the lime
content (4% above the optimum lime content) in case of the weathered soil and were not changed in case of the organic silt (see Fig. 4.1 a).

The ratio of the CBR-value of the lime-, fly ash-, and lime/fly ash-stabilized soil to that of the untreated compacted soil is known as the CBR-gain factor. The CBR-gain factors (due to the addition of the optimum lime content) of the tertiary clay, the organic silt, and the weathered soil are 13.1, 5.25, and 3.17, respectively. The final consistency (quality) of the mixtures is excellent, good, and fair, respectively (see Table 3.4 and Fig. 4.2).

The addition of fly ash contents resulted in an increase in the CBR-values for the three studied soils. Fly ash-tertiary clay mixtures have the highest CBR-values and fly ash-weathered soil mixtures have the lowest values, at the same fly ash contents.

The CBR-values of tertiary clay-fly ash mixtures increased with increasing the fly ash content until 20%. Above 20% fly ash (for example 25%), the CBR-value decreased. Similar behavior was obtained at measurement of the unconfined compressive strength (see chapter 3.4.1).
The CBR-values of both fly ash-organic silt and -weathered soil mixtures are relatively lower than the CBR-values of fly ash-tertiary clay mixtures, at the same fly ash contents. Fly ash-organic silt mixtures have the CBR-values relatively higher than the CBR-values of fly ash-weathered soil mixtures, at the same fly ash contents. CBR-values for both fly ash-organic silt and -weathered soil mixtures increased with increasing the fly ash content.
CBR-gain factors of fly ash-organic silt mixtures are slightly higher than the CBR-gain factors of fly ash-tertiary clay mixtures, at the same fly ash contents. CBR-gain factors of fly ash-weathered soil mixtures are lower than the factors of both fly ash-organic silt and –tertiary clay mixtures, at the same fly ash contents. CBR-gain factors (due to the addition of the optimum fly ash content) of tertiary clay, organic silt, and weathered soil are 8.57, 14.31, and 9.44, respectively (see Fig. 4.2).

CBR-gain factor of both the organic silt and the weathered soil is higher than the factor of tertiary clay. The final consistency (quality) of optimum fly ash-tertiary clay, -organic silt, and -weathered soil mixtures is good, good, and excellent, respectively (see Table 3.4).

The addition of lime and fly ash together led to a dramatic increase in the CBR-values for the three studied soils compared to the addition of lime and fly ash separately. The CBR-values of tertiary clay-lime/fly ash mixtures are higher than both weathered soil- and organic silt-lime/fly ash mixtures. CBR-gain factors (due to the addition of the optimum lime/fly ash content after pH-method) of tertiary clay, organic silt, and weathered soil are 10.17, 11.00, and 8.24, respectively. CBR-gain factor (due to the addition of the optimum fly ash with small percentage of lime) of tertiary clay (2.5\%L/16\%F), organic silt (2\%L/20\%F), and weathered soil (3\%L/35\%F) is 18.96, 12.56, and 14.67, respectively (see Fig. 4.2). The final consistency of tertiary clay, organic silt, and weathered soil–lime/fly ash mixtures is excellent, good, and excellent, respectively (see Table 3.4). CBR-values increased with increasing lime/fly ash ratio. The optimum lime/fly ash ratio of tertiary clay, organic silt, and weathered soil is 0.16, 0.15, and 0.14, respectively. Above the ratios of 0.16 and 0.15 for both the tertiary clay and the organic silt, respectively (about 1 lime: 6 fly ash by weight) and above the ratio 0.14 (about 1 lime: 7 fly ash by weight) for the weathered soil, the CBR-values of the soils-lime/fly ash mixtures decreased (see Fig. 4.3).

This means that the increment of lime percentage above 16, 15, and 14\% of the fly ash weight for the tertiary clay, the organic silt, and the weathered soil, respectively resulted in a decrement of the CBR-values of the soil-lime/fly ash mixtures.

### 4.2.2 Effect of curing time

Soil-fly ash and soil-lime/fly ash mixtures, for the three different tested soils, were prepared and cured for periods of 7, 28, 56, and 180 days to evaluate the effect of long-term curing on the CBR-value of the treated stabilized soils. All the specimens were prepared at the optimum water content.
The effect of curing time on CBR-value of soil-fly ash and soil-lime/fly ash mixtures is illustrated in Figure 4.4. The CBR-values of both soil-fly ash and soil-lime/fly ash mixtures increased with curing time in case of the three tested soils.

CBR-values of tertiary clay- and weathered soil-lime/fly ash mixtures were strongly affected by the long-term curing compared to tertiary clay- and weathered soil-optimum fly ash mixtures. Organic silt-optimum fly ash mixtures were strongly affected by curing time.
compared to organic silt-lime/fly ash mixtures. In general, the CBR-values of fly ash- and lime/fly ash-stabilized weathered soil were slightly affected by the long-term curing in comparison to CBR-values of both stabilized-tertiary clay and –organic silt.

CBR-values of tertiary clay-lime/fly ash mixture increased dramatically with the long-term curing compared to weathered soil- and organic silt-lime/fly ash mixtures (see Fig. 4.4 and Tables 3.1, 3.2, & 3.3).

4.3 Conclusions

* In the case of lime-stabilization process, the addition of optimum lime content (according to pH-method) resulted in an increment of the CBR-values of the three studied soils. Tertiary clay has the highest CBR-values, whereas weathered soil has the lowest CBR-values. CBR-value of lime-stabilized tertiary clay increased with an increase in the lime content continually (2 and 4% above the optimum lime content). Another behavior of both the organic silt and the weathered soil was obtained, in which case the CBR-values increased at 2% above the optimum lime content. CBR-values, at 4% above the optimum, decreased slightly in the case of weathered soil and were not changed in the case of organic silt. CBR-gain factors (due to the addition of the optimum lime content) of tertiary clay, organic silt, and weathered soil are 13.1, 5.25, and 3.17, respectively. The final consistency (quality) of the mixtures is excellent, good, and fair, respectively.

* In the case of fly ash-stabilization process, the addition of fly ash led to an increase in the CBR-values for the three tested soils. CBR-values of both the organic silt and the weathered
soil increased with an increase in the fly ash content. CBR-values of tertiary clay increased with the increase in fly ash content from 8 to 20%. Above 20% fly ash (for example 25%), the CBR-values decreased. Similar behavior was observed at qu-measurement. The CBR-gain factors of fly ash-organic silt mixtures are slightly higher than the CBR-gain factors of fly ash-tertiary clay mixtures, at the same fly ash contents.

* In the case of lime/fly ash-stabilization process, the addition of lime and fly ash together increased the CBR-values of the three tested soils strongly compared to the addition of lime and fly ash separately. Lime/fly ash-tertiary clay mixtures have CBR-gain factors higher than lime/fly ash-organic silt and –weathered soil mixtures. The optimum ratio of lime to fly ash is 0.16 in case of the tertiary clay and 0.15 in case of the organic silt (about 1 lime : 6 fly ash) and is 0.14 (about 1 lime : 7 fly ash) in case of the weathered soil.

* CBR-values and CBR-gain factors of both the fly ash- and the lime/fly ash-mixtures, for the three tested soils, were improved and increased through the long-term curing. The influence of curing time was strong on the lime/fly ash-stabilization process compared to the fly ash-stabilization process, especially in case of the tertiary clay where the increase of CBR-value and CBR-gain factors was dramatic. The effect of curing time on the fly ash- and lime/fly ash-stabilization process in the case of weathered soil was weaker than the effect in the case of both tertiary clay and organic silt.