TEMPERATURE AND TIME EFFECTS ON THE SHEAR STRENGTH OF SAND STABILIZED WITH CATIONIC BITUMEN EMULSION

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The paper describes laboratory investigations of the effects of temperature, strain rate, and specimen age on the shear strength of sand stabilized with cationic bitumen emulsion. The shear strength parameters C_u and ϕ_u were determined using standard triaxial testing equipment. The effect of mixing, curing, and testing temperatures on both C_u and ϕ_u were separately resolved. The effect of increased temperature during either mixing or curing was to improve particle coating and cohesive strength. Triaxial tests carried out over a wide range of strain rates showed that C_u for identical specimens increased as the nth power of the rate of strain, where n is a constant that varies with the bitumen content, whereas ϕ_u decreased linearly with the logarithm of strain rate. Unconfined compression tests on specimens of varying ages showed that strength increased significantly with age and that, at ages exceeding 12 weeks, specimens having the highest bitumen content had the highest strength. The effect of decreasing testing temperature, increasing strain rate, and increasing specimen age were analogous in increasing the cohesive strength measured.

•IT HAS BEEN the purpose of the investigation described here to study the effect of various environmental factors on the strength properties of sand stabilized with cationic bitumen emulsion. This paper represents an extension to the initial study (1) of the influences of processing procedures on the strength of the same material.

Bituminous mixes generally have viscoelastic properties, and their behavior is consequently very much temperature- and time-dependent. It can be expected, therefore, that a road pavement composed partially or wholly of a bituminous mix will be markedly affected by its temperature environment. In addition, resistance to deformation will depend not only on the magnitude of the wheel loads but also on their speed of travel.

The temperature of a road surface may change considerably during the course of a day or from season to season, and, because of the heat-absorption properties of black bituminous materials, the temperature of a road surface may be much higher than that of the ambient air (2, 3). This variable environment will be the one in which the bituminous mix will be cured after laying and in which it will later be subjected to traffic loading. In a laboratory study, the effect of temperature on strength has been studied by varying (a) the curing temperature and (b) the testing temperature. In addition, because some control over the temperature at which mixing is carried out may be exercised in the field, a further study of the effect of mixing temperature has been included.

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REVIEW OF PREVIOUS WORK

The authors are aware of only one study of environmental effects on the strength of emulsion-stabilized sand (4), but some information is available in the literature on the properties of other types of sand-bitumen mixes.

It is well known that increasing the temperature of a mix will improve workability and the resulting aggregate surface coating. Conversely, the stiffness and strength of manufactured material will decrease markedly with increasing temperature and/or decreasing rate of testing, and vice versa. Gregg et al. (5) used the method of reducing variables or the time-temperature superposition principle to investigate the combined effect of these two factors on sand-bitumen mixes. They found that the cohesion (C_u) dropped significantly with increasing temperature and/or decreasing rate of testing, whereas no consistent change in the angle of shearing resistance (ϕ_u) was observed. Marais (4), using a vane shear apparatus on bituminous sand mixes, found that the shear strength was not much affected by the rate of vane rotation but that it decreased significantly with increasing temperature. Abdel-Hady and Herrin (6) found that the unconfined compressive strength of soil-asphalt did not increase appreciably with increasing strain rate, from 0.125 to 2 percent per minute, whereas a rapid increase occurred when the testing rate was increased from 25 to 75 percent per minute.

Most investigators found that both the total strength and the cohesive component of strength dropped with increasing temperature, due to the change in binder viscosity, and apparently increased with faster rates of testing, due to viscosity effects. However, there appears to be controversy concerning the effect of temperature and testing rate on the angle of shearing resistance ϕ_u. For example, Nijboer (7) found that ϕ_u was independent of the rate of testing but that it increased with temperature. He concluded that a harder bitumen was a better "lubricant" than a softer one. Goetz and Chen (8) found no consistent effect on ϕ_u values when changing the rate of testing, and neither did Gregg et al. (5). On the other hand, McLeod (9) reported a decrease of several degrees in ϕ_u values for an eightfold increase in testing rate from 0.05 to 0.4 in. per minute on 8-in.-high specimens.

The authors disagree with Nijboer's conclusions on the grounds that the range of testing rates he studied was too narrow (maximum was only 4 times the minimum). Furthermore, he used only one specimen over a range of lateral pressures in a closed-system triaxial cell, which led to excessive deformation at the higher cell pressures. This test would not be so reliable as a standard triaxial series of tests on fresh specimens.

There appear to be few records of investigations into the effect of mixing and curing temperatures on bituminous sand mixes. Although emulsions are normally mixed without heating, it is important to know what effect the ambient temperature may have or to discover whether slight heating may affect the strength of the product.

Aging of bituminous mixes involves a gradual evaporation of volatiles and an oxidation of the bitumen, causing hardening. There is also evidence that the adhesion of bitumen is improved with time. Hallberg (10) showed that the contact angle of bitumen with aggregate decreased with time until it reached zero. Marais (4, 11) found that the in situ vane shear strength of bituminous sand mixes increased with age at a decreasing rate.

In the case of sand stabilized with emulsion, a major increase in strength will occur as the water content is evaporated. Thereafter, increases in strength due to the factors mentioned above may take place.

It has been observed that mixes of cationic emulsion and sand are seldom perfect in that the particles are always improperly coated with bitumen. Some of the bitumen is left in the form of globules immediately after mixing. Compaction pressures and subsequent applied pressure will have the effect of squeezing these globules and extruding them between particles, thereby improving distribution. However, the authors believe there is another process of redistribution that is a function of time and temperature. Under the influence of gravity and surface tension forces, the bitumen phase tends to flow and redistribute itself. This process may continue under the usual range of air temperatures over an extended period of time, but under elevated temperature conditions the process is accelerated. The idea of improved adhesion by redistribution is supported by Hallberg's findings that a decrease in contact angle takes place with time. The result of improved coating and adhesion is an increase in the cohesive strength of the material. It may also have a marginal effect on the angle of shearing resistance, for the redistribution of bitumen may increase the number of points of direct contact between particles, particularly if pressure is simultaneously applied to the material. Such a concept of rearrangement of particles was referred to by Nevitt (12) and by Wood and Goetz (13), although not directly proved.

It will be shown by the results of the tests described below that the strength of cationic emulsion-stabilized sand is improved if it has previously been subjected to elevated temperatures during either mixing or curing.

LABORATORY INVESTIGATION

The Cationic Emulsions Used

The first part of the investigation of the properties of sand stabilized with cationic emulsion (1) had shown that emulsions containing base bitumens of high viscosity gave the highest strength. As a result, all the tests described in the present paper were carried out using only 2 types of emulsion, both of which contained low-penetration bitumen.

One emulsion was made up with a Shell Mexphalt bitumen of 60/70 penetration and required 0.75 percent addition of a cationic emulsifier known as Redicote E-11 (14), hereafter referred to as "RE-11". This was supplied by Armour Hess Chemicals Ltd. The other emulsion, prepared by Lion Emulsions Ltd., hereafter referred to as "Lion", contained a base bitumen of 40/50 penetration. The properties of both emulsions are given in Table 1.

Properties of the Sand

The same sand (without addition of fillers) as described in the earlier work (1) was used. It was a Leighton Buzzard sand having a fairly uniform grading, as shown in Figure 1, representative of the natural grading of a desert sand and similar to many naturally occurring deposits of sand that would normally be difficult to stabilize. Its properties are given in Table 2.

TEMPERATURE AND AGING EFFECTS

Effect of Ambient Temperature on Shear Strength

The separate effects of mixing temperature, curing temperature, and testing temperature on the strength of air-dry cured sand-emulsion mixes were investigated. Strength was measured by means of undrained triaxial tests, and the parameters C_u and ϕ_u were determined in the usual way.

Effect of Mixing Temperature

Five separate batches of sand containing 9 percent RE-11 60/70 emulsion and 3.5 percent additional water were mixed in an electrically heated laboratory asphalt mixer. Each batch was mixed at a different temperature, using a preset control governed by a thermostat, set in turn to temperatures varying from 18.5 to 77 C (65 to 171 F).

The sand was placed in the mixer and preheated. Both the emulsion and water were separately heated to the same temperature. When mixing, water was added first followed by the emulsion. Each batch was mixed for 2 minutes, then vibration-compacted in the standard way described in the authors' previous paper (1). After 7 days of air-dry curing in the laboratory at 18 C (64 F), 4 specimens produced from each batch were tested under cell pressures of 0, 20, 40, and 60 psi respectively and at an ambient temperature of 18 C. The values of C_u and ϕ_u determined from the Mohr diagrams obtained are plotted in Figures 2 and 3.

Over the range of temperatures from 15 to 45 C (59 to 113 F) it is evident that there was very little increase in strength. The dry density achieved by compaction increased, and this apparently had the effect of increasing the angle of shearing resistance (ϕ_u).

Table 1. Properties of emulsions used.

Property	Redicote E-11	Lion
Percent emulsifier	0.75	—
Base bitumen viscosity, penetration	60/70	40/50
Emulsion viscosity, ° Engler	15	5.4
Specified bitumen content, percent	58	56
Measured bitumen content, percent	57	55
pH	4.9	—
Typical residue on No. 100 mesh, percent	0.25	0.05

Table 2. Properties of Leighton Buzzard sand used in study.

Property	Amount
Chemical Composition	
Silica, percent	98.81
Alumina, percent	0.35
Other metal oxides, percent	0.54
Ignition loss, percent	0.20
	99.90
Physical Properties	
Maximum dry density (B.S. 1377), pcf	101.5
Optimum moisture content (B.S. 1377), percent	10.5
Surface area, cm^2 per g	119.5
Specific gravity	2.65
Angularity (Loudon 1953)	1.1
Sphericity	0.82
Minimum porosity (at 0 percent moisture content), percent	31.3
Uniformity coefficient	1.95
Internal porosity, percent	0.4 to 1.4

Figure 1. Grading of sand used in the investigation.

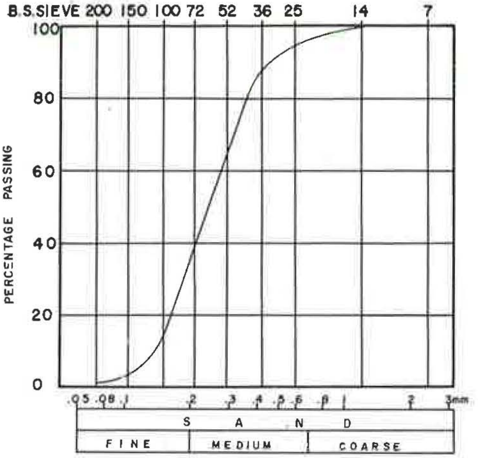
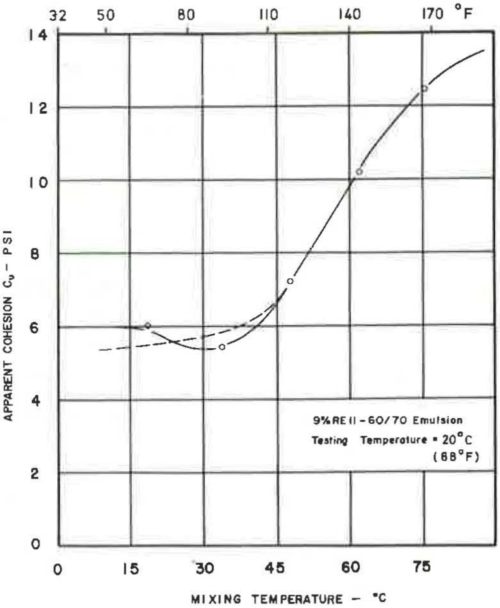


Figure 2. Effect of mixing temperature on the apparent cohesion of 9 percent emulsion-stabilized sand.



Over this temperature range no improvement in bitumen coating of the particles was visually observable.

At temperatures above 45 C (113 F) it was visibly evident that coating of particles improved with increasing temperature, and the cohesive strength of specimens increased accordingly. Presumably because of this improved coating, interparticle friction was reduced with a consequent slight reduction in ϕ_u.

Figure 4 shows the outer appearance of the groups of specimens mixed at different temperatures. It appears to be significant that the magnitude of cohesive strengths measured was in the same order as darkness of appearance. For example, group 5 in Figure 4, which is darkest, gave the highest cohesive strength, while group 2, which is the lightest and most speckled, yielded the lowest strength.

It is clear that the changes in cohesion are of much greater significance than the changes in the angle of shearing resistance, so that specimens that are unconfined or subjected to low confining pressures may have their strengths doubled by preheating constituents prior to mixing.

Effect of Curing Temperature

Experiments investigating the influence of curing temperature were carried out on 2 sets of specimens. One set of 19 was prepared using 5 percent Lion 40/50 emulsion with 3 percent additional water, and 7 specimens were prepared using 6 percent RE-11 60/70 with 4 percent water. These were compacted to the dry densities corresponding to those achieved by standard AASHO compaction during previous tests. The samples were subdivided into 6 groups of 4, consisting of 3 Lion emulsion and one RE-11 and a 7th group of 2. Each group was then cured at a different temperature in various ovens for a period of 10 hours. All the specimens were then removed from their warm environment and allowed to cure in the laboratory atmosphere at 18 C for the remainder of a 7-day period.

The Lion emulsion specimens were finally tested by undrained triaxial apparatus, using three different confining pressures, while the RE-11 specimens were tested in unconfined compression. The actual testing temperature was 20 C (68 F).

As may be seen from the plot of maximum deviator stress against curing temperature shown in Figure 5, an increase of curing temperature resulted in a significant increase in shear strength. From Figure 6, it may be deduced that this increase was predominantly due to an increase in cohesion C_u, although a total increase of ϕ_u amounting to 4 deg was also observed. Of note is the fact that at temperatures above 60 C (140 F) relatively little increase in strength occurred.

Effect of Testing Temperature

Three sets of specimens were prepared using 6, 9, and 13 percent RE-11 60/70 emulsion. These were mixed and compacted with 4, 3.5, and 3 percent additional water respectively. These quantities of water had been found from previous compaction tests to be the optimum amounts required to produce maximum dry density when the standard vibration compaction (1) was applied. After standard compaction, the specimens were dry-cured for 7 days at laboratory temperature before being mounted in a triaxial apparatus housed in a temperature-controlled cabinet.

The inside air temperature of the cabinet was capable of being adjusted to within ± 0.5 C (0.9 F) of any desired temperature between -10 C (+14 F) and 50 C (122 F). Temperature measurements by thermistors buried in the middle of the emulsion-stabilized specimens showed that it took between 3 and 5 hours for the temperature of the specimens to equilibrate with the ambient air temperature in the cabinet. The samples having the highest bitumen content took the longest time to equilibrate. On the basis of these tests, specimens were left in the temperature cabinet for a minimum period of $3\frac{1}{2}$ hours before being tested. Cell pressures were applied by compressed air, as this could be quickly heated or cooled. All specimens were tested at a rate of strain of 1.1 percent per minute.

Figure 7 shows the effect of testing temperature on measured strength in terms of maximum deviator stress. The rate of reduction of strength with respect to tempera-

Figure 3. Effect of mixing temperature on the compaction and angle of shearing resistance of 9 percent emulsion-stabilized sand.

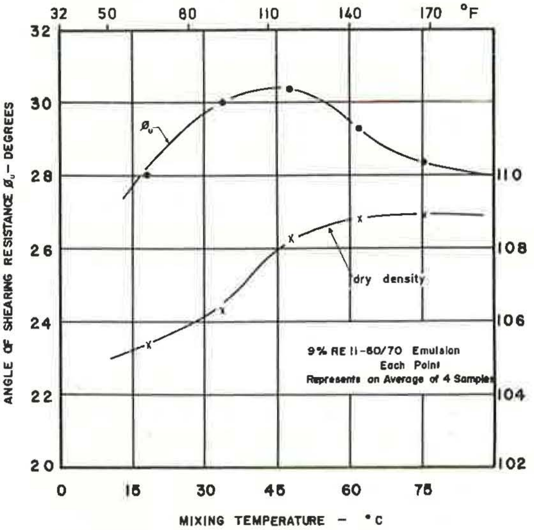


Figure 4. Effect of mixing temperature on coating.

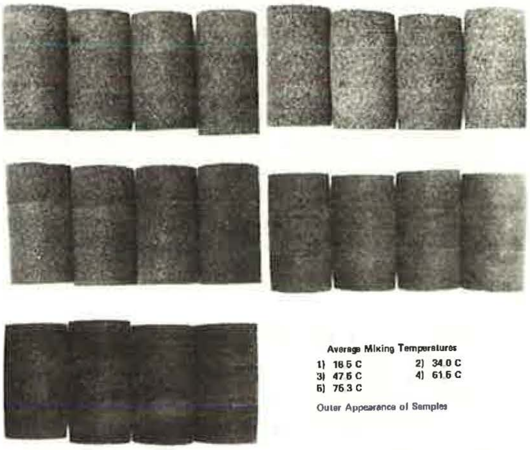


Figure 5. Effect of curing temperature on shearing resistance at different cell pressures.

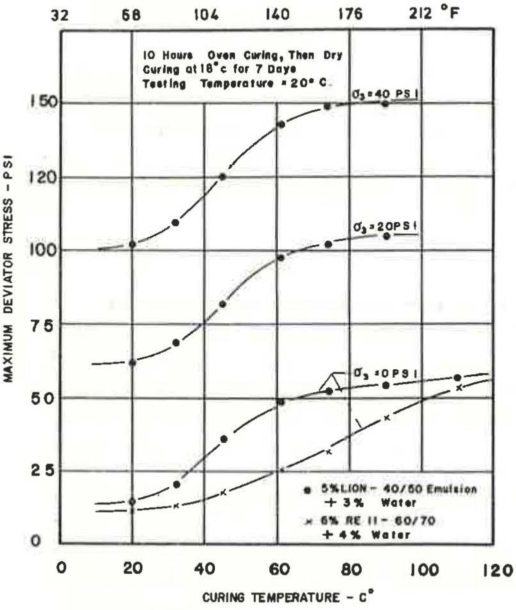
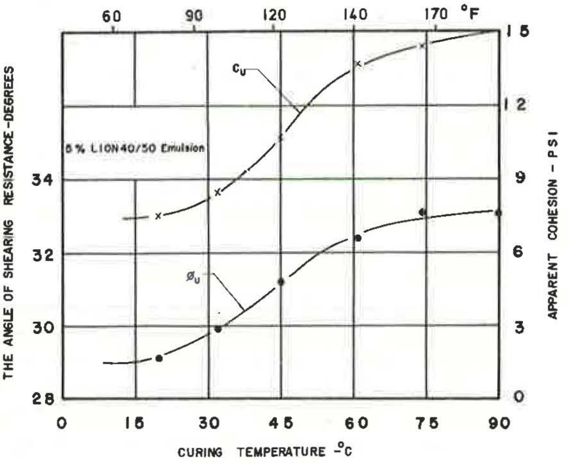


Figure 6. Effect of curing temperature on shear strength parameters measured at 20 C.



ture increase was greatest over the low-temperature ranges, while above 35 C (95 F) there was little change in strength.

The components of shear strength C_u and ϕ_u were calculated from the intercept and slope of the Mohr-Coulomb failure envelopes obtained. Figure 8 shows the influence of bitumen content on the apparent cohesion C_u measured at different temperatures. It is interesting to observe that at a given temperature there is an optimum bitumen content for maximum cohesion. As the temperature is decreased, the optimum increases. The optima corresponding to the various temperatures are of course only the optima for the particular set of test conditions. If the age of the specimens had been greater or their curing temperature higher, the optima would also have been higher. At the low temperature of -5 C (+23 F) within the range of emulsion contents tested, the strength increases as the bitumen content is increased.

Figure 9 shows the effect of bitumen content on the angle of shearing resistance ϕ_u at various temperatures. The decrease of ϕ_u with increased bitumen content was small, even at high temperatures, but the reduction in ϕ_u of about 6 deg with a change of temperature from -5 C to +50 C was unexpectedly large.

The reason for these observed changes in angle of shearing resistance prbably lies in the structural behavior of the material during shear. At high temperatures, the viscosity of the bitumen is low, and the bitumen is less capable of preventing individual particles from moving relative to one another. As shear stress is applied, consolidation or negative dilation takes place; pore bitumen pressures may even be developed, and the shear strength is affected detrimentally. At low temperatures, however, the bitumen, being more viscous, can reduce the mobility of individual particles. The bitumen has the effect of binding groups of particles into pseudo-aggregates of sizes larger than the individual sand particles. Instead of consolidation taking place, dilation may occur. Since additional work is done in dilation, this would have the effect of increasing the apparent angle of shearing resistance. Because no measurements of volume change were made, this theory can only be treated as conjecture at present.

Effect of Rate of Testing

Three batches of specimens were made up containing 6, 9, and 13 percent RE-11 60/70 emulsion with 4, 3.5, and 3 percent additional water respectively. The specimens were compacted as described elsewhere (1) to the dry densities corresponding to those achieved by compacting the materials for 2 minutes with a Kango hammer in 3 equal layers within a standard AASHO mold. All specimens were dry-cured for 7 days in the laboratory atmosphere before being tested by undrained triaxial apparatus. A wide range of testing rates was selected and the rates of deformation set on the machine were 0.00036, 0.04, 0.045, 0.3 and 2.4 in. per minute. By testing specimens in the usual way values of C_u and ϕ_u were obtained.

When the cohesion values were plotted on a log-log graph against rate of strain (Fig. 10), a linear relationship was obtained for all three emulsion contents. The results may be expressed in the form

$$C_u = C_1(\dot{\epsilon})^n \qquad (1)$$

where C is the undrained cohesion, C_1 is the undrained cohesion at a rate of strain of 1 percent per second, $\dot{\epsilon}$ is the rate of strain with respect to time in seconds, and n is an index dependent on the bitumen content and is the slope of the log-log plot of cohesion-strain rate.

A linear regression analysis of the results yielded the following values of the parameters in Eq. 1:

Emulsion Content (percent)	Bitumen Content (percent)	C_1 (psi)	n	Correlation Coefficient
6	3.54	18.09	0.3437	0.9907
9	5.14	20.67	0.3125	0.9970
13	7.67	31.13	0.3955	0.9945

Figure 7. Effect of testing temperature on the maximum deviator stress measured in triaxial tests on stabilized sand containing various proportions of emulsions.

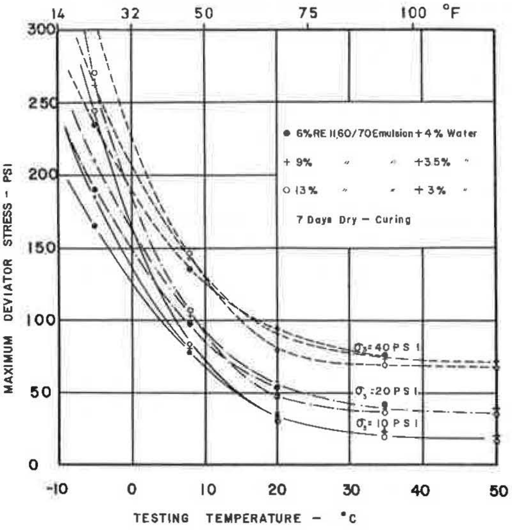


Figure 8. Effect of bitumen content on apparent cohesion measured at various temperatures.

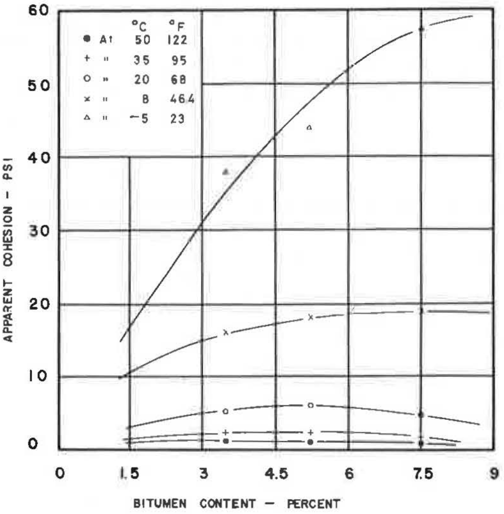


Figure 9. Effect of bitumen content on the le of shearing resistance measured in the xial test at various testing temperatures.

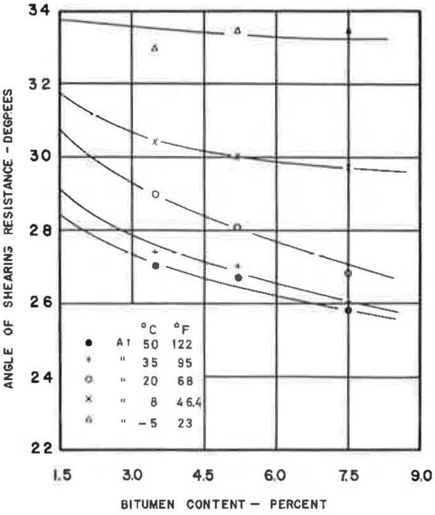
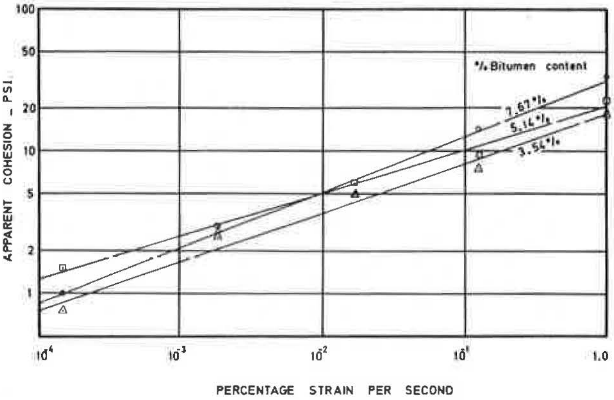


Figure 10. Effect of rate of strain on the apparent cohesion.



The enormous increase in measured cohesion with testing rate was due to the effects of the viscosity of the bitumen. Differentiating C_u with respect to $\dot{\epsilon}$ gives

$$\frac{\partial C_u}{\partial \dot{\epsilon}} = n \cdot C_1 \cdot (\epsilon)^{-(1-n)} \qquad (2)$$

This shows that the increase in strength with respect to increase in strain rate is not constant but that it decreases as the strain rate increases. The material is therefore not behaving as a true Newtonian liquid.

Figure 11 shows a plot of C_u against bitumen content and illustrates that at very slow rates of strain there appears to be an optimum bitumen content. As the rate of strain is increased, the optimum bitumen content increases to such an extent that within the range of contents tested, the highest C_u values are obtained with the highest bitumen contents. There is a striking similarity between this graph and Figure 8, and it is clear that increasing the rate of strain has the same effect on the measured cohesion as decreasing the temperature.

The angle of shearing resistance was also affected by the testing rate. A slight drop in ϕ_u values was observed as the testing rate was increased. If ϕ_u is plotted against log strain rate (Fig. 12) it is seen that the value of ϕ_u can be expressed by the equation

$$\phi_u = \phi_1 - m \log_{10}(\dot{\epsilon}) \qquad (3)$$

where m is the tangent of the slope of the graph and ϕ_1 is the angle of shearing resistance at a rate of strain of 1 percent per second.

The results indicate that over the wide range of strain rates tested the angle of shearing resistance fell about 4 deg.

Linear regression analysis of the results yielded the following values of the parameters in Eq. 3:

Emulsion Content (percent)	Bitumen Content (percent)	ϕ_1	m	Correlation Coefficient
6	3.54	27.846	0.8010	0.9971
9	5.14	26.29	0.9874	0.9999
13	7.67	23.99	1.0807	0.9997

At slow rates of strain the bitumen binder would have time to flow from between particles being pushed together by applied stress. This flow would result in an increased degree of particle interlock, giving increased frictional resistance. In contrast, at high strain rates very little flow of bitumen could take place and the frictional resistance would not be so improved. This may explain the reduction in ϕ_u with strain rate. Figure 13 illustrates that the angle of shearing resistance falls almost linearly with bitumen content irrespective of the rate of strain applied. It is clear, however, that the reductions in strength due to changes in ϕ_μ are small compared with the increases in C_u when the strain rate is increased, and the net effect is a significant increase in total strength.

Effect of Aging

An investigation of the effect of aging of specimens for periods of up to 3 months has already been published (1). The results are again included here in the form of Figure 14 for completeness. Specimens for this investigation were mixed with 6, 9, and 13 percent RE-11 60/70 emulsion to which was added 4, 3.5, and 3 percent of additional water respectively. All specimens were given standard vibration compaction and then were dry-cured in the laboratory for periods varying from 1 to 12 weeks before being compression-tested.

From the strengths measured at 7 days it appears that 5 percent bitumen content is the optimum for maximum strength. However, after 2 weeks the optimum bitumen

Figure 11. Effect of bitumen content on apparent cohesion measured at various rates of strain.

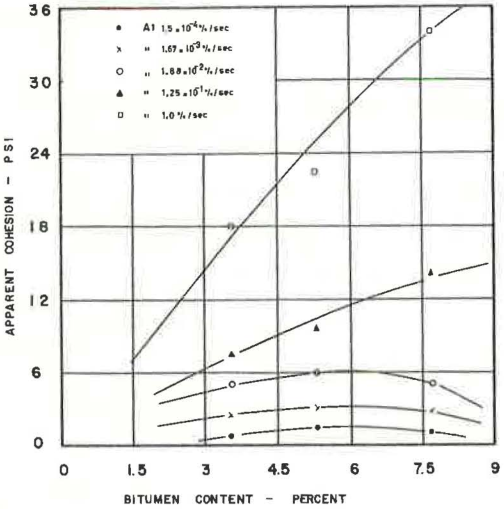


Figure 12. Effect of rate of strain on the angle of shearing resistance.

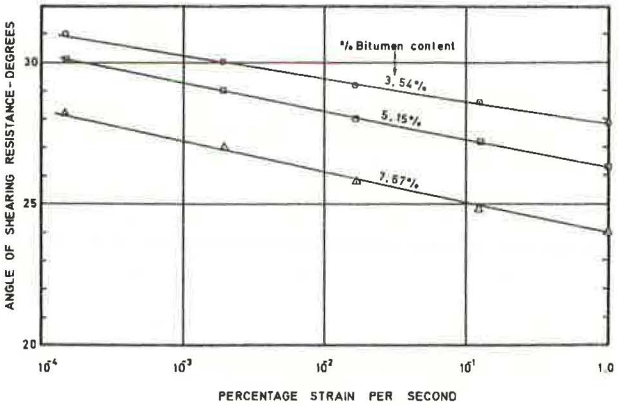


Figure 13. Effect of bitumen content on angle of shearing resistance at various rates of strain.

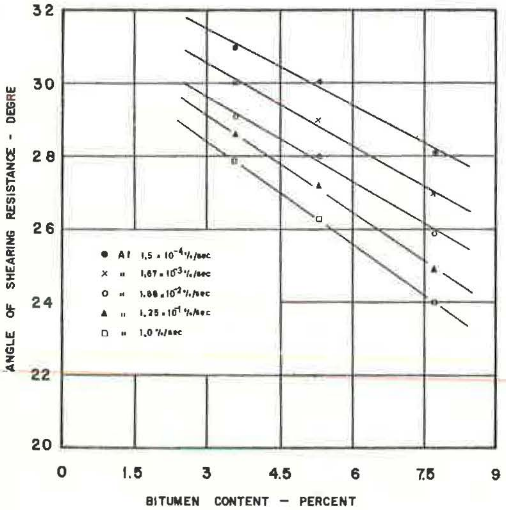
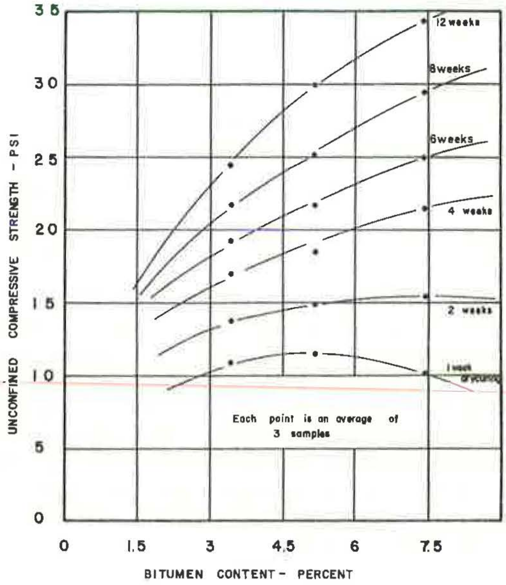


Figure 14. Effect of age on the strength of stabilized sand containing various bitumen contents.



content appears to be 7.5 percent. After a further period of time the optimum appears to be higher. Hence, within the range of bitumen contents tested, the more emulsion added, the higher will be the long-term strength under conditions of dry-curing.

The reader should notice the marked similarity between Figures 8, 11, and 14, all of which are plots of cohesive strength to a base of bitumen content. This provides convincing evidence of the analogous effects of decreasing testing temperature, increasing rate of strain, and aging, all of which produce a higher measured cohesive strength.

CONCLUSIONS

Preheating aggregate and cationic emulsion to temperatures between 45 and 75 C_u (113-167 F) just prior to mixing them together had the effect of significantly increasing the ultimate cohesive strength of dry-cured compacted specimens. The preheating effect on the angle of shearing resistance was not important. Judging by the visual appearance of compacted specimens, the higher temperatures had the effect of improving particle surface coating and mix uniformity.

Curing temperature was shown to have a significant effect on cohesive strength. This increased with curing temperature over the range from 20 to 90 C (68-194 F) tested. The angle of shearing resistance also was beneficially affected, although to a lesser extent than cohesion.

The effect of increasing the testing temperature was to reduce both C_u and ϕ_u. The optimum bitumen content to give maximum measured cohesive strength was increased by decreasing the testing temperature. At -5 C (+23 F), the highest bitumen content tested (7.5 percent) gave the highest cohesive strength. The extent of reduction in ϕ_u was 6 deg over the whole range of testing temperatures.

The cohesive strength of stabilized sand was shown to be proportional to the nth power of the strain rate, where n varied between 0.3125 and 0.3955 for the bitumen contents tested, while ϕ_u fell linearly with the logarithm of the rate of strain. Again, the optimum bitumen content to give maximum measured cohesive strength was increased by increasing the rate of strain. At high strain rates, the highest bitumen content tested gave the highest cohesive strength in a way analogous to reducing the temperature.

Aging of specimens had a significant effect in increasing the shear strength, and the optimum bitumen content to give maximum unconfined compressive strength was increased by increasing specimen age. At 12 weeks, the specimens having the highest bitumen contents gave the highest strength.

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