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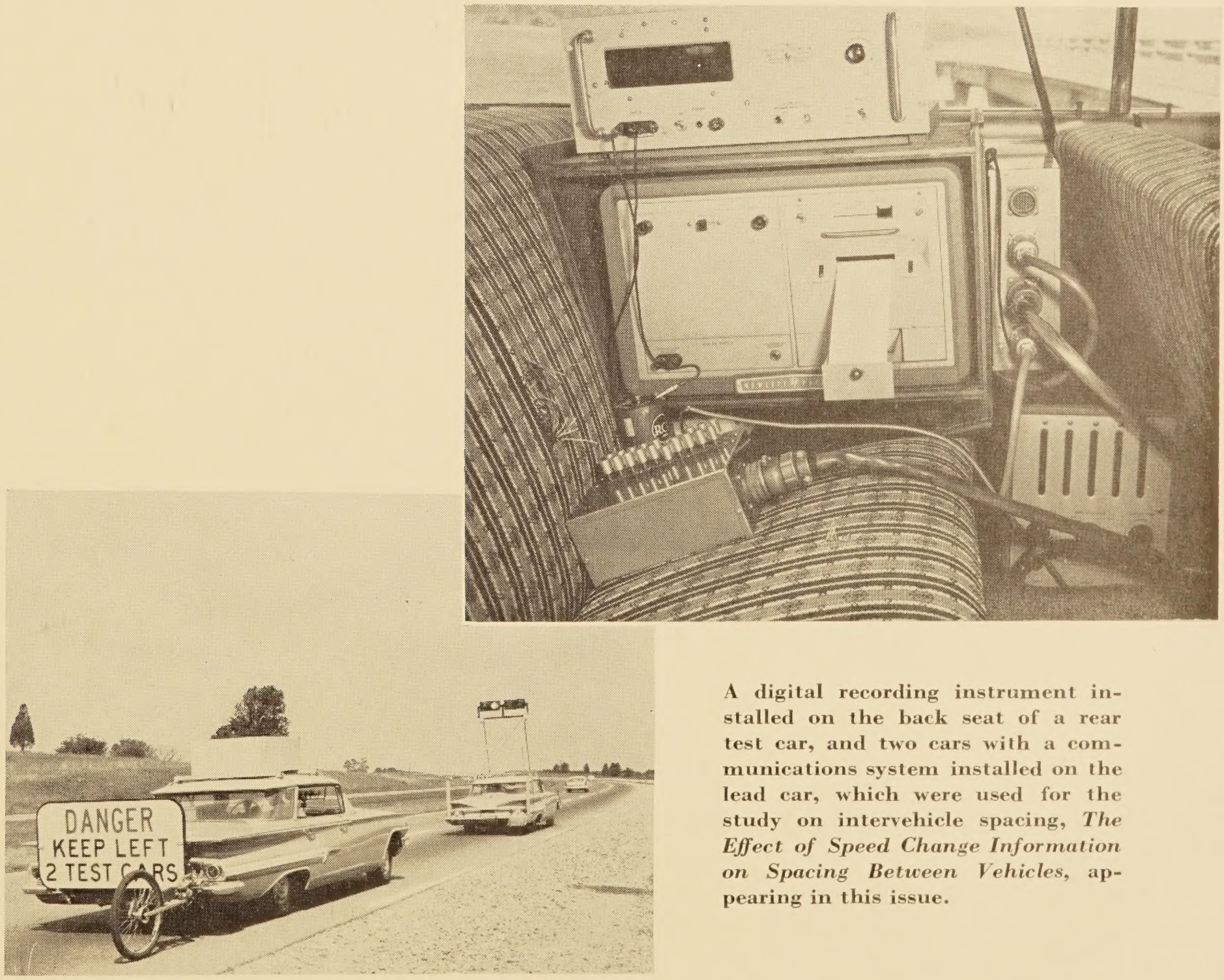

A digital recording instrument installed on the back seat of a rear test car, and two cars with a communications system installed on the lead car, which were used for the study on intervehicle spacing, *The Effect of Speed Change Information on Spacing Between Vehicles*, appearing in this issue.

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IN THIS ISSUE

U.S. DEPARTMENT OF COMMERCE
LUTHER H. HODGES, Secretary

BUREAU OF PUBLIC ROADS
REX M. WHITTON, Administrator

The Effect of Speed Change Information on Spacing Between Vehicles

BY THE TRAFFIC OPERATIONS DIVISION
BUREAU OF PUBLIC ROADS

Reported [1] **by RICHARD M. MICHAELS, Research Psychologist,**
and DAVID SOLOMON, Highway Research Engineer

Variations in the spacing maintained between vehicles has been attributed primarily to the drivers' reactions to changes in the speed of the preceding vehicle. On this basis, tests were conducted, with two- and three-car queues, in which a communications system was employed to transmit advance speed change information to the driver of a rear test car. Test data were analyzed to determine the effectiveness of the communications system—the test drivers' responses were studied to determine whether intervehicle spacing had been modified as the result of transmission of the advance speed change information.

This study was undertaken because intervehicle spacing is considered to be one of the more important factors affecting the stability of car-following patterns and thereby influencing the volume of traffic that can be moved on a highway. Analysis of the two-car test data indicated that use of a communications system, similar to the one employed in the study reported here, could increase the traffic-carrying capacity of a highway. From analysis of the three-car test data, it was noted that most of the potential effect of the communications system had been eliminated by interposition of a third car. With use of the communications system, a relation between advance warning time and the distance headways was noted for two-car queues.

Variability in headways was substantially reduced when the driver of a rear car had advance information on the speed changes. The variability noted in driver responses, to information provided by the communications system, indicates that the stability of intervehicle spacing is greatly influenced by fluctuations in the individual driver's psychological state.

Introduction

RECENT RESEARCH (*1*) [2] indicates that variations in spacing between vehicles in a queue are determined primarily by the drivers' reactions to changes in speed of the vehicle ahead and, secondarily, by the distance between vehicles. When a change in speed is imposed in the lead car, the driver of the second car, in order to maintain his spacing, reacts to the change in speed—not the change in distance. Thus, he changes the speed at which his car is traveling to eliminate any difference in speed between the cars. The stability of the operation depends therefore upon the length of time elapsing from the lead vehicle's change in speed to its detection by the driver of the following car, as well as his ability to modify the speed of his car.

As pointed out by Brown (*2*), estimates of speed changes ultimately depend on the driver's ability to detect changes in visual angle (the angle, at the eye of the observer, subtended by the boundaries of an object), which governs the time a driver requires to detect changes in the speed of the lead vehicle. Because of human limitations, small changes in visual angle and hence in speed are not detectable. Consequently, in normal car-following patterns a time lapse occurs between the initiation of a speed change in the leading car and its detection by the driver of the following car. To a large extent, much of the instability of the queues as demonstrated by other car-following studies could have resulted from the relative insensitivity of the drivers to small changes in visual angle.

Also contributing to variance in spacing of cars in a queue is the fact that the driver of a following car has no prior knowledge of the occurrence of any acceleration or deceleration of the preceding vehicle nor the magnitude of that change of speed. (Display of brake lights or hand signals may warn of deceleration.) Therefore, the following driver may be expected to adopt a spacing to compensate for his uncertainty stemming from these two factors: his inability to detect small changes in visual angle and his inability to anticipate the change in speed.

Two methods for improving the stability of car-following are suggested by consideration of the foregoing analysis: (1) To improve the drivers' abilities to detect changes in visual angle, or (2) to provide the drivers of following cars with information about changes in the speed of the lead vehicle before such changes are initiated. The second method provided the basis for the study discussed in this article.

Possible predictions on driver behavior

From the foregoing analysis several hypotheses are possible about the behavior of the driver of a car, when he is given information on the type and magnitude of each change in speed to be made in the lead vehicle.

First, the driver of the following car, by responding to this advance information, should be able to compensate for changes in speed in the lead vehicle by beginning his maneuver prior to the onset of the change. The degree of compensation effected should depend upon the interval of time between the driver's receipt of the information and the onset of the speed change in the lead vehicle.

Second, because the driver of the following car does not have to rely on his ability to detect changes in speed, he will not have to maintain a spacing commensurate with his maximum ability for such detection. Consequently, it is reasonable to assume that the average headway during a constant speed operation would be less with a communications system than without it. (Headway is the time or space interval between two vehicles traveling the same route. For precise reference, the terms distance headway and time headway are used in this article.)

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[1] This article was presented at the 41st annual meeting of the Highway Research Board, Washington, D.C., January 1962.

[2] References cited by italic numbers in parentheses are listed on page 235.

Third, the variance in headway between cars in a constant speed operation should be decreased when communication is employed.

An attempt was made in this study to determine whether, in a simple pattern of one car following another, intervehicle spacing would be modified when drivers were provided advance information on speed changes.

Summary and Conclusions

From this study with two- and three-car queues, it was determined that the effect of the use of the communications system on the spacing between two vehicles varied with the speed at which they were moving; its use had little effect when the speed was 36 m.p.h. (miles per hour) but resulted in a large reduction in distance headway when the speed was 54 m.p.h. However, when another vehicle was interposed, making a three-car queue, the communications system's effect on distance headway was nearly eliminated at all speeds. During constant speed operations, at any of the three speeds used, the variance in headways between the two cars was significantly reduced by the communication of speed change information to the test drivers. The transmission of this information approximately 3 seconds prior to initiation of the speed change by the lead car permitted maintenance of the most uniform headways.

On the basis of data collected during the study, it is concluded that communication of advance speed change information from one driver to another is an extremely complex problem. Further, no simple or direct means exists for transmitting advance speed change information that will result in a universal or predictable modification of headway patterns in car following.

Recording Instruments and Their Use

A stadimeter (a range-finding device) was used in this study to measure the distance headway between a pair of vehicles. The stadimeter operates on the same principle as the sextant in that two images are brought into coincidence by use of a rotating mirror. Because use of the stadimeter requires specification of some dimension of the target whose range is sought, the dimension was marked by two brightly painted targets mounted on the rear bumper of the lead vehicle (fig.1). The mounting of the stadimeter in the second car is shown in figure 2.

Operation of stadimeter

The stadimeter operator viewed the lead car through the ring sight on the right of the instrument. While looking at one target, he slowly rotated the mirror on the left of the sight by turning the crank, on the left side of the instrument, until the image of the second target coincided with that of the first. The hand crank also was geared to drive a precision potentiometer so that the angular displacement of the mirror was translated into a voltage change. The distance in feet between the vehicles is inversely related to the angular rotation of the mirror. By use of a calibration procedure the voltage change was converted to the distance in feet.

The task of the stadimeter operator was to keep the two targets in coincidence during the run. For distances of more than 50 feet, tracking error generally was less than 5 percent, which was adequate for purposes of this study. A digital recording system, described in a report by Hopkins (*3*), was employed to store the data. Headway readings were converted to digital form by use of a digital voltmeter, were read out, and were stored by use of a digital printer. The speed of the rear vehicle also was determined, digitized, and stored in the printer. An equipment operator in the rear car manually coded the following listed data into the printer: Each speed change made by the lead vehicle, its speed at the beginning and ending of each maneuver, and the time each maneuver was started and ended.

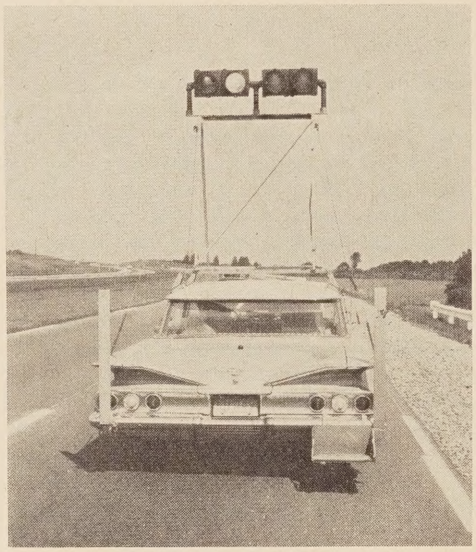

Figure 1.—Lead car with overhead signals and targets on rear bumper.

By means of radio equipment installed in the two vehicles, the lead car observer could notify the equipment operator in the following car what change of speed was to occur and when the change began and ended. This was done only when no visual communication signal was given. As the equipment operator used head phones, the driver of the following car could not hear these messages.

Four rates of acceleration were used for each series of maneuvers: +1, +3, −1, and −3 m.p.h./sec. (miles per hour per second). The interval between each maneuver in a series was either 15, 30, or 45 seconds in duration. An automatic recycling timing system had been installed in the lead vehicle to specify the individual maneuver to be undertaken, the advance warning time (if any) to be signaled to the following car, the duration time of the maneuver, and the interval between the beginning of each maneuver in the series and the beginning of the next. By means of cue lights on the dashboard, the driver of the lead car was notified when to begin and end each maneuver. In general, the driver's control in making speed changes was accurate to within 5 percent.

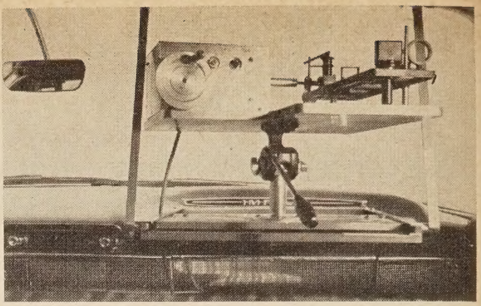

Figure 2.—Stadimeter mounted in rear car.

The information display for the driver of the following car consisted of four traffic signal units with white lenses, 8 inches in diameter, mounted above the lead vehicle, as shown in figure 1. Each signal unit represented one of the four possible speed change maneuvers. The size of the signal units and the height at which they were mounted above the lead vehicle were dictated by possible conditions of grade, curvature, and length of queue that might be employed for any particular study to be made with this display.

Site of Study

A 7-mile portion of Interstate Highway 70, located between Gaithersburg and Rockville, Md., and considered typical of a rural freeway, was selected as the study site. This freeway is a four-lane divided highway on which there is full control of access. Each of the four lanes, constructed of bituminous concrete, is 12 feet wide. Although the shoulders generally are 10 feet wide (8 feet of gravel and 2 feet of grass), a small part of the study site has gravel shoulders 12 feet wide. The dividing median is a grass strip 50 feet wide.

The speed limit at the test site is 60 m.p.h. and only a few vehicles were observed exceeding this limit. Typical of a rural freeway, the design speed for this section of the highway is 70 m.p.h.; maximum gradient is 3 percent, except for a length of 1,000 feet where the grade is 3.5 percent; and the maximum horizontal curvature is one degree.

The daily traffic volume on the section of the highway used for this study was about 10,000 vehicles. While the study was underway, daytime traffic averaged about 600 vehicles per hour or about 300 vehicles per hour on each one-way roadway—a relatively low volume of traffic for a freeway near a large metropolitan area. This low traffic volume and the high-type design characteristics of the highway were the principal reasons for selection of this study site. These factors made it possible to drive at a reasonably wide range of speeds for the required length of time with little interference to or from other traffic.

Procedures

Either two or three vehicles were used in the test runs for this study in which headways were measured for the rear cars, which were driven by test drivers. In addition to the test driver, the rear car carried the stadimeter operator (observer) and the equipment operator.

Drivers

Seven drivers were used for this study. Four were summer employees of the Bureau of Public Roads; their ages ranged from 18 to 24 years; all had had at least 2 years of driving experience. The other test drivers were the experimenters conducting the study. All seven drivers participated in the test runs made with the two cars but only the four test drivers participated in the three-car test runs. To isolate any effects of possible bias, the primary analyses of the data collected from two-car tests were made only for runs by the four test drivers. Because analyses of the data indicated responses of all seven drivers to be quite comparable, information collected from all two-car tests was used for some of the subsidiary analyses.

Before the beginning of each test run, each test driver was given the following instructions: "Assume you are driving in rush hour traffic. Assume that vehicles are in the left lane beside you as well as behind you. Drive as you would in this type of traffic by keeping pace with the vehicle ahead so as to minimize the possibility of other vehicles weaving in front of you."

Two-car studies

In the test procedure with two cars, the speedometer of the rear vehicle was covered and the tail lights of the lead vehicle were disconnected for all test runs. The lead car carried out precise maneuvers and the headway was measured between the two vehicles.

Before the beginning of each test run, the study's signal system was explained to the test driver. He was told that when the signal lamp on the extreme left of the lead car was lighted a fast acceleration would be made, and that the next three signals would indicate fast deceleration, slow acceleration, and slow deceleration, respectively. The signal lamp was lighted prior to the onset of the speed change for a period of time determined by the preselected warning condition and remained lighted until completion of the maneuver.

A run included 16 speed changes—four repetitions each of maneuvers from 36 to 45 m.p.h., from 45 to 36 m.p.h., from 45 to 54 m.p.h., and from 54 to 45 m.p.h. Just prior to the start of each run, the test driver was also informed as to which of the five test conditions would be used: without communications or with communications at one of the four warning times (0, 1, 3, or 5 seconds). For the "without communications" condition, the signal lamps were not used and the test driver received no information concerning the maneuver to be executed. When the run was made with communications, the signal system was used to indicate the magnitude of the speed change to be made during each maneuver (+1, +3, −1, or −3 m.p.h./sec.), as well as to show the preselected warning time conditions.

All runs were started when both vehicles were traveling at a speed of 45 m.p.h. The programing device was then activated in the lead vehicle and one of the four preprogramed speed changes was presented on the appropriate signal lamp. At the end of the first maneuver of each run, the lead vehicle was traveling at a speed of either 36 or 54 m.p.h. Therefore, speed changes for the second maneuver of a run required acceleration from 36 m.p.h. or deceleration from 54 m.p.h. Thus, the test driver's uncertainty as to the speed change that would be presented was only half that he experienced when the next maneuver was to be made from a speed of 45 m.p.h.

At the end of each run, another warning time condition was randomly selected; the test driver was informed of the new condition; and another run was executed by the two cars. This procedure was repeated until the test driver had completed five runs in succession, one for each warning condition. Each of the seven test drivers made five successive runs and the entire procedure was repeated four times so that each driver completed four runs for each of the five test conditions.

Three-car studies

In the three-car studies, the signals for indicating speed changes and warning time were mounted above the first vehicle, which initiated all maneuvers, but the targets for headway measurement were mounted on the rear of the second car. The test driver operated the third car. Speedometers of both the second and third cars were taped over. The procedure for measuring the intervehicle spacing between the second and third cars was the same as that used for test runs with two cars. Runs were made with only three test conditions rather than five: without communications and with communications during which the warning time was either 1 or 5 seconds. Only the four test drivers were used for tests with the three cars and test runs for each of the three conditions were repeated by each driver three times. The drivers of the second and third cars were given instructions similar to those given for the two-car runs.

ANALYSES

Choice of Headway at Constant Speed

Four independent variables were studied in the analysis of headway: (1) Speed, (2) driver, (3) run, and (4) type of communications. Data were obtained for all 240 combinations of the four variables in the case of the two-car following situation. For the three-car data analysis, the 0-second and 3-second warning time conditions were omitted.

Information was obtained from all possible combinations of the independent variables for the time intervals between maneuvers; that is, when the two vehicles were traveling at some constant speed. Samples of information, consisting of the record of speed and headway of both vehicles, were taken at one-second intervals by the digital recording system. To eliminate any time coherence among the sample points, additional samples were taken from recorded data at five-second intervals. In general, 10 to 15 samples were taken from each of the two speeds of 36 and 54 m.p.h., which were maintained during four periods of time in each test run, and 20 to 40 samples were taken during the eight periods of time the speed was constant at 45 m.p.h. In order to obtain a completely balanced block design for the analysis of variance, a final sampling of 10 random observations was made for each of the three speeds of each run.

Analysis of Variance Data for Two-Car Runs

An analysis of variance was performed on the two-car data. Four main variables of three speeds, four drivers, four runs, and five communications conditions were used. For each of the 240 combinations of these variables, 10 headway measurements were employed, thus making 2,400 headway observations. The analysis demonstrated that not only were the main variables significantly different at the 0.01 level, but also that all

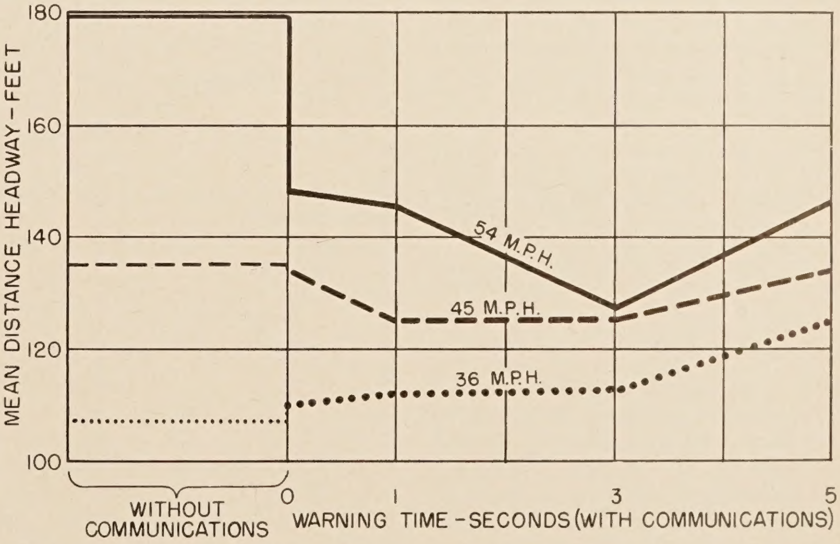

Figure 3.—Mean distance headways maintained in two-car runs without and with communications.

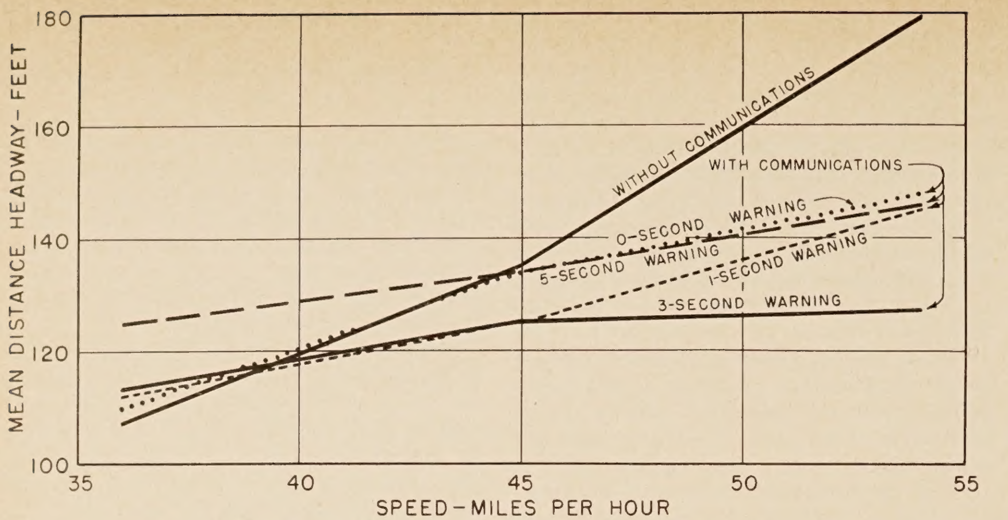

Figure 4.—Effect of warning time on mean distance headways in two-car runs at each test speed.

six first order, four second order, and the third order interaction terms were significant at the 0.01 level. As a check on the sampling procedure, an additional analysis of variance was performed on all the variables for one run (speed, driver, type of communications), and identical results of the analysis were obtained: all terms were significant at the 0.01 level.

Interaction of speed and warning time

For more detailed analysis of the effects of the communications system, data were separated on the basis of speed. At the highest speed of the runs, 54 m.p.h., consideration of the data reveals a very significant reduction in mean distance headways when the communications system was used. This information is graphically presented in figure 3. With communications, the mean distance headways varied from a minimum of 127 feet to a maximum of 148 feet; without communications, the mean headway was 179 feet. True headway distances (from the rear end of the lead car to the rear end of the rear car), used for this analysis of the two-car test data, were obtained by adding a constant of 10 feet to the recorded headway, which the stadimeter had measured from the dashboard of the following vehicle to the rear bumper of the leading vehicle. At the lowest speed used in the study, 36 m.p.h., headways were no shorter with the communications system than without it. At the intermediate speed of 45 m.p.h., the headways began to decrease with use of the communications system.

Effect of warning time

Warning times had a considerable effect on the headways maintained, as shown in figure 3. With a 3-second advance warning time at 54 m.p.h., the drivers maintained minimum headways. At 45 m.p.h. minimum headways appeared to have been maintained within the range of a 1- to 3-second advance warning time. But at a speed of 36 m.p.h., no differences in headway occurred when the warning time was less than 3 seconds. However, with the longest advance warning time of 5 seconds, headways maintained at all three speeds were much longer than those maintained with the 3-second warning time. At 54 m.p.h., headways maintained with a 5-second warning time were about the same as those maintained with a 1-second warning time and were 15 percent longer than those maintained with a 3-second warning.

In figure 4, the relationship of headway to speed is illustrated with warning time as the parameter. Without communications, distance headways increased sharply as speed increased. For each of the four test run conditions with communications, distance headways increased less as the speed increased. Most noteworthy is the fact that the shortest headways were maintained with the 3-second warning time and, more importantly, were practically independent of speed. Therefore, 3 seconds may be considered the optimum warning time.

A further comparison of the relation of speed to headways maintained was made by converting the distance headways (fig. 3) to time headways for each speed range. These respective time headways were plotted against speeds for each test condition. As shown in figure 5, when maneuvers were performed without communications the time headways increased at the highest speed: but for each of the four warning-time conditions with communications, the time headways decreased with increased speeds. The lowest value of time headway was obtained from the data on the 3-second warning time at the speed of 54 m.p.h. Note the relation of time headway shown (fig. 5) for the condition without communications and that shown for the 3-second warning time. At a speed of 36 m.p.h., the difference in time headways shown for the two communications conditions is not statistically significant, but at speeds of 45 and 54 m.p.h. the time headways obtained with a 3-second warning time were significantly shorter than those from the condition without communications. At a speed of 54 m.p.h. this reduction was 30 percent.

Summary of Tabulated Data

A tabular summary of all data collected during this study for the two-car runs is shown in table 1. Each entry represents the average of 40 observations of data collected for all four runs averaged together.

The time headways for this study (shown in table 1) were calculated from the distance headways, as noted previously. For the calculation, it was assumed that the lead and

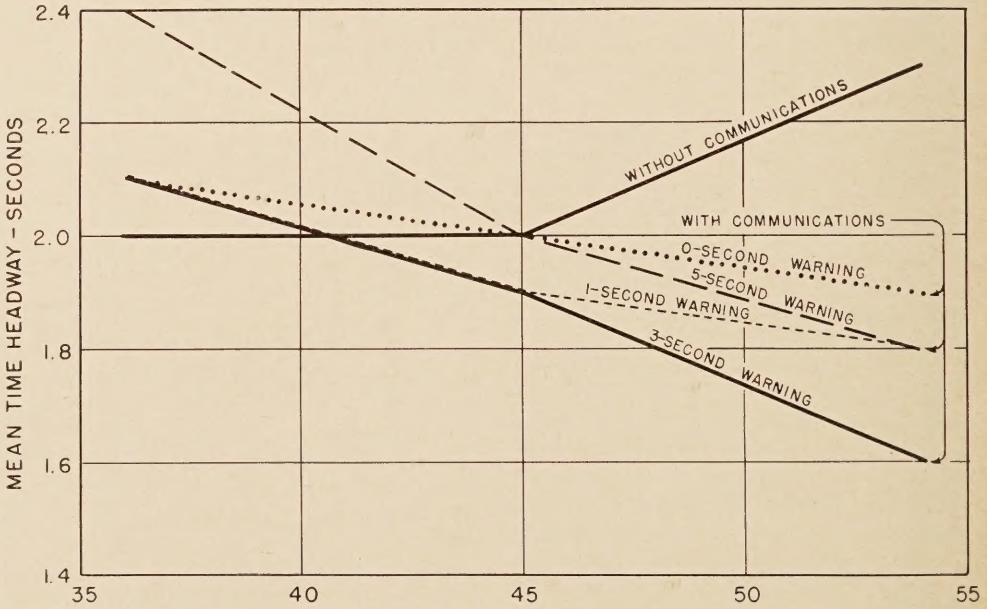

Figure 5.—Mean time headways maintained in two-car runs with communication of several warning times.

rear vehicles were traveling at an identical speed of either 36, 45, or 54 m.p.h. Because the drivers of the lead cars were extremely careful to maintain precise speed relationships, this assumption was close to the actual situation.

Table 1.—Mean distance and time headways maintained by each of four drivers at three speeds with and without communications in two-car runs[1]

Warning time	Driver A		Driver B		Driver C		Driver D		Average	
				36 MILES PER HOUR						
Seconds	*Feet* [3]	*Seconds*	*Feet* [3]	*Seconds*	*Feet* [3]	*Seconds*	*Feet* [3]	*Seconds*	*Feet*	*Seconds*
None [2]	92	1.7	113	2.1	116	2.2	106	2.0	107	2.0
0	111	2.1	120	2.3	111	2.1	97	1.8	110	2.1
1	116	2.2	108	2.0	130	2.5	94	1.8	112	2.1
3	114	2.2	116	2.2	127	2.4	94	1.8	113	2.1
5	132	2.5	132	2.5	134	2.5	102	1.9	125	2.4
				45 MILES PER HOUR						
None [2]	114	1.7	165	2.5	149	2.3	112	1.7	135	2.0
0	131	2.0	173	2.6	124	1.9	110	1.7	134	2.0
1	122	1.8	127	1.9	131	2.0	119	1.8	125	1.9
3	114	1.7	136	2.1	142	2.2	108	1.6	125	1.9
5	129	2.0	152	2.3	148	2.2	107	1.6	134	2.0
				54 MILES PER HOUR						
None [2]	155	2.0	224	2.8	182	2.3	157	2.0	179	2.3
0	142	1.8	189	2.4	131	1.7	129	1.6	148	1.9
1	128	1.6	176	2.2	144	1.8	136	1.7	145	1.8
3	117	1.5	137	1.7	143	1.8	112	1.4	127	1.6
5	120	1.5	189	2.4	156	2.0	118	1.5	146	1.8

[1] Headways in two-car runs were measured from rear end of lead car to rear end of rear car.
[2] None indicates no communication at all.
[3] Indicates average of four runs.

A large variability in response of the four drivers both to speed and the type of communications employed is evident from consideration of the data. Because of these significant differences in driver reactions, the averaged data shown in the summary column of table 1 should be interpreted with extreme caution; these data, of course, represent a combination obtained from different populations.

As noted previously and as shown in figure 4, the mean distance headways when the warning time was 3 seconds were practically the same at all three speeds—between 113 and 127 feet; this range of only 14 feet is also shown in table 1. The range in mean distance headways over the three speeds for the other four communications conditions varied from 21 to 72 feet; generally, the same range was noted in the headways maintained by each driver. Test data also revealed that, among the four drivers, the relationship of mean time headways noted for conditions of no communications and the 3-second warning time is consistent (table 1). Although the absolute values of the time headways for the four drivers differ significantly, the change in time headway as a function of speed is similar in that the time headways for the 3-second warning time decreased sharply as the speed increased.

Communications Markedly Reduce Variation in Headway

Data collected from runs made by the three experimenter drivers were added to the data for runs by the four test drivers for a further analysis of the variation in headways. Standard deviations of distance headways were calculated for each of the three speeds under two test conditions, without communications and with the optimum warning time of 3 seconds. These calculations are shown in table 2. When data from the no communications condition and the 3-second warning time communication condition were compared, a reduction in standard deviation was noted for 19 of the 21 comparisons, and only one increase in standard deviation occurred. In most cases, the reduction was substantial and in 15 of the comparisons the differences were statistically significant. The median ratio of the standard deviation over all three speeds for all seven test drivers was 0.57, a reduction of 43 percent. In other words, communications reduced the variation in headway very substantially.

Analysis of Speed Changes During a Maneuver

Another analysis of data obtained from test runs with two cars was made concerning the speed changes carried out by the test drivers during the maneuvers. Although the limitations of the data processing system prevented a precise analysis of the time course of the changes in speeds, it was possible to determine some of the effects of the communications system by the control responses of the test drivers. An example of typical responses is shown by the curves in figure 6. When the speed change for the lead car was a slow acceleration from 45 to 54 m.p.h. at the rate of 1 m.p.h./sec., the test drivers tended to respond so that the position of the rear vehicles changed from leading to lagging as the warning time decreased from 3 seconds to 0 seconds, to a condition of no communications.

This analysis also revealed some indication that the test or rear car drivers were using the warning intervals to begin the speed changes; such a response is shown clearly by the curve in figure 6 for the 3-second warning time. The drivers of the rear cars had closed on the lead vehicles during the initial part of a maneuver, when the optimum warning time of 3 seconds was employed, then at some point toward the end of the maneuver had eased up on the accelerator thereby increasing the distance headways. The deceleration at the end of the maneuvers tended to show a great variability among the drivers and from one trial run to another.

Analysis of Data for Three Cars

For the portion of the study made with three cars, data on the effect of speed change information on intervehicle spacing were collected from only three test runs made by each of the four drivers.

For three cars, the headways were measured from the rear of the second car to the rear of the third car; communications were transmitted from the lead car. The third or rear car was driven by a test driver.

An analysis of variance also was carried out on the data collected from test runs of the three cars. With one exception, all terms were significant at the 0.01 level; the third order interaction term was significant at the 0.05 level.

Table 2.—Standard deviations of distance headways and their ratios for each of seven drivers at three speeds in two-car tests

Driver	36 miles per hour—			45 miles per hour—			54 miles per hour—		
	Without communications	With communications	Ratio	Without communications	With communications	Ratio	Without communications	With communications	Ratio
	Feet	*Feet*		*Feet*	*Feet*		*Feet*	*Feet*	
A	16	16	1.00	24	21	0.88	24	15	[1]0.63
B	21	14	[1].67	25	17	[1].68	27	13	[1].48
C	78	16	[1].21	67	16	[1].24	67	24	[1].36
D	68	28	[1].41	56	30	[1].54	60	16	[1].27
E	15	10	[1].67	18	24	1.33	20	17	.85
F	11	9	.82	18	16	.89	40	11	[1].28
G	14	8	[1].57	26	12	[1].46	29	13	[1].45
Median	----------	----------	[1].67	----------	----------	[1].68	----------	----------	[1].45

[1] Significantly different from 1.00 at the 0.05 level or less.

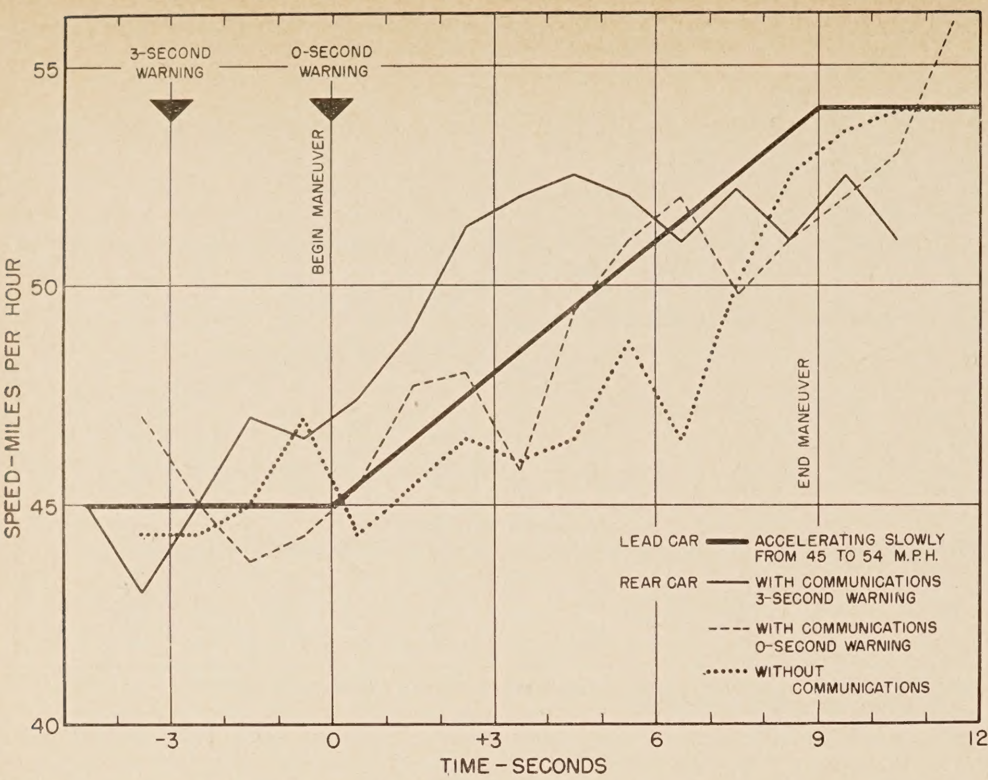

Figure 6.—Example of test driver responses during a maneuver in two-car runs. (Note anticipatory response for the 3-second warning time.)

Analysis of three-car data showed that the mean headways were considerably less than those calculated for two cars, as can be seen by comparison of information detailed in table 3 with that shown in table 1. In general, time headways were about one-half second shorter for all communications conditions in three-car test runs. Moreover, the influence of the communications system was far less effective in causing the drivers to reduce following distance than it had been during the two-car runs.

With three cars and all three communications conditions, a small increase was noted in the mean distance headways as the speeds increased from 36 to 54 m.p.h. However, decreases in mean time headways occurred both with and without communications; this decrease in time headways as speeds increased was larger when the test runs were made with communications. Table 3 contains headway data collected for three-car test runs.

When the interposition of a vehicle between the lead car and the rear car is considered, the 1-second warning time for the three-car test runs appears to have had an influence on the headways maintained by the test drivers that is probably equivalent to the influence of the 3-second warning time condition during two-car test runs. From examination of the test data presented in the summary column of table 3, it can be seen that with the 1-second warning time a range of only 16 feet in distance headways occurred for three-car runs between the speeds of 36 and 54 m.p.h. When the 5-second warning time condition was employed the range in headways increased to 24 feet, and when the condition was without communications it increased to 34 feet. The 16-foot minimum range with the 1-second warning time is consistent with the lowest range in distance headways of 14 feet recorded at all three speeds for two-car tests with a 3-second warning time condition.

Table 3.—Mean distance and time headways maintained by each of four drivers at three speeds with and without communications in three-car runs [1]

Warning time	Driver—								Average	
	A		B		C		D			
36 MILES PER HOUR										
Seconds	*Feet* [3]	*Seconds*	*Feet* [3]	*Seconds*	*Feet* [3]	*Seconds*	*Feet* [3]	*Seconds*	*Feet*	*Seconds*
None [2]	78	1.5	73	1.4	73	1.4	91	1.7	79	1.5
1	90	1.7	71	1.3	97	1.8	88	1.7	87	1.6
5	97	1.8	85	1.6	77	1.5	99	1.9	90	1.7
45 MILES PER HOUR										
None [2]	92	1.4	100	1.5	84	1.3	107	1.6	96	1.5
1	99	1.5	84	1.3	92	1.4	107	1.6	96	1.5
5	110	1.7	103	1.6	89	1.3	103	1.6	101	1.5
54 MILES PER HOUR										
None [2]	107	1.4	113	1.4	96	1.2	136	1.7	113	1.4
1	109	1.4	97	1.2	91	1.1	116	1.5	103	1.3
5	104	1.3	130	1.6	93	1.2	128	1.6	114	1.4

[1] Headways in three-car runs were measured from rear end of second car to rear end of third car.
[2] None indicates no communication at all.
[3] Indicates average of three runs.

Discussion of Data Analyses

Analyses of the data collected during this study indicate that substitution of an alternate information path for judgment of speed changes is possible, and that drivers are able to utilize a very simple coding scheme (communications system), at least in a two-car following situation. In other words, the driver of a car generally adapts his following distance according to the advance information he has about the changes in speed to be made by the lead car and his ability to make corresponding compensatory control changes in the speed of his own vehicle.

The major contribution of the signal system was its provision of information that permitted the test driver to begin his compensatory speed change before the onset of the speed change in the lead vehicle. Thus, a driver used the actual change in speed of the lead vehicle as a feedback on his speed control responses. This is illustrated by the curves in figure 6.

Assistance from the communications system received by the test driver was least during an acceleration maneuver. Although limitations in the recording system precluded a complete analysis of the total effect of the communications system, some indication was noted of a lower rate of acceleration or deceleration with the display of speed change information than without it. However, considerable variation in acceleration or deceleration occurred during individual maneuvers, and this apparently resulted from the necessity for a driver to make visual angle discriminations and, more importantly, the predictions of future speed of the vehicle preceding his own. The experimental system employed in this study, of course, added nothing that a driver could use for such purposes.

The warning time—that is, the interval between display of the visual signal and the initiation of the speed change of the lead vehicle—was also observed to be an important factor in the following pattern adopted by the test driver in the rear car during constant speed operations. Analysis of the data showed that, dependent on the speed at which the test cars were traveling, minimum headways and minimum variance were obtained when the interval of warning time was between 1 and 3 seconds. The warning time obviously was not employed solely as a reaction time but rather was used as a total response time of the system, encompassing perception and translation into control and vehicle responses.

With the most favorable warning conditions, consideration of the analyses shows that spacing maintained between vehicles became independent of speed and indicated that another following system had been established by the driver. Although this system was speed dependent, the drivers employed a different information processing mode and adapted the headways to the remaining constraints on following—mostly random variations in speed between two vehicles.

Verification of Predictions Based on Hypothesis

On the basis of the hypothesis for this study, it was predicted that average distance headways between maneuvers would be less with communications than without. Analyses of the data from two-car tests indicated that this was true at the two higher speeds of 45 and 54 m.p.h. but not true for the low speed of 36 m.p.h.

The prediction that the variability in headway would be reduced when the driver of the rear vehicle had prior information about speed changes to be initiated by the driver of the lead vehicle was confirmed by the analyses of test data.

Traffic capacity of freeway lane

Consideration of the data collected during test runs with two cars seems to indicate that a communications system could increase the traffic capacity of a freeway lane. As noted previously (fig. 5), without communications the minimum time headways occurred at speeds below 45 m.p.h. and averaged 2.0 seconds. If the time headways for a single lane of traffic average 2.0 seconds for one hour, the total traffic volume would equal 1,800, which approaches the volume of 2, 000 vehicles per hour that has been widely accepted as the possible capacity for a freeway lane. Few highways in the United States are known to carry a greater volume, and other studies have shown that the minimum headways and maximum capacity usually are obtained when vehicles are traveling at speeds of less than 45 m.p.h.

When communications were added, the speed-headway relationships changed markedly and the mean time headways decreased as the speeds increased. With the 3-second optimum warning time, as illustrated in figure 5, time headways of 1.6 seconds were maintained at 54 m.p.h., the highest speed used in this study. Were time headways to average 1.6 seconds for one hour at 54 m.p.h., the traffic capacity for a single freeway lane would exceed a volume of 2,200 vehicles per hour. Thus theoretically, utilization of a communications system, providing information similar to that of this study, would permit a one-third increase in the traffic capacity of a freeway lane at a speed of 54 m.p.h. This increase was derived from comparison with the study data obtained when the test condition was without communications and the time headway at 54 m.p.h. was 2.3 seconds, which would permit a volume of only 1,600 vehicles per hour.

Therefore, what seems to be a fairly simple communications system would appear, by extrapolation, capable of generating a sizeable increase in the capacity of a freeway at the higher speeds. However, analysis of the three-car data does not allow such a conclusion. The addition of an interposed vehicle eliminated most of the benefits to be obtained from a communications system, as implied by the analysis of data from two-car tests.

As shown in the final column of table 3, without communications the average time headways between the second and third cars were considerably shorter at all three speeds than between the first and second cars with communication of a 3-second warning time. Furthermore, with communication of a 1-second warning and at speeds of 54 m.p.h., the time headways in three-car runs were only 0.1 second less than those maintained during the runs without communications. This elimination of most of the benefits, obtained by use of the communications system, with the interposition of a vehicle in a three-car queue may be attributed to several factors.

First, in a line of traffic a natural tendency exists to maintain stability of speed and spacing. Thus any speed change imposed by the lead vehicle may be expected to be compensated for by the drivers of successive vehicles as they perceive and thereby progressively reduce the effect of the speed change.

Second, if the driver of the third vehicle observed the speed change behavior of the first vehicle directly, he might very well receive as much advance warning as he would from the communications system. That such does take place has been suggested in a report by Forbes (*4*).

Third, automobiles in a line represent a very loosely coupled system, subject to considerable random fluctuations. A communications system such as the one used for this study should have a decreasing effect upon the responses of the driver as the distance increases between the communications system and his vehicle. Any interposed vehicle prevents the following driver from directly coupling himself to the source. The driver, of necessity, must compensate primarily for the behavior of the vehicle immediately preceding his and secondarily for the behavior of those further ahead in the line. In essence, in the multiple car-following situation, the speed change information display represents little more than a cue informing a driver that some change of speed will be made in the preceding line of traffic.

Variability of drivers' responses

Another clear-cut fact obvious from analyses of these data is that a high degree of variability occurs both within and among drivers' responses. Considerable differences were noted in their responses concerning time relations and optimum following, minimum variance conditions, and at different speeds. Although the differences in mean headways with a 3-second warning were quite small at all three test speeds, the analysis of variance showed a significant difference among speeds. As no systematic differences in variance occurred among the three speeds, it seems reasonable to conclude that the significance arises from inter- and intra-driver response changes from run to run. It would appear, then, that the driving system is greatly influenced by the moment-to-moment fluctuations in a driver's psychological state, as well as by his more stable behavioral characteristics. Sensitivity to such subtle qualities is not a characteristic of efficient man-machine systems.

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A Supplementary Study of Concrete Produced by 34-E Dual-Drum Pavers

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This article presents information obtained from tests made during construction of an Arkansas road project on the relation of mixing time to the strength of portland cement concrete produced in a 34-E dual-drum paver. Objective of this supplementary study was to gain data to check against results shown by similar tests made during construction of 16 projects by 13 State highway departments; test results from the previous study were summarized in the April 1960 issue of this magazine.

It was believed that insufficient data had been obtained from the earlier study, especially concerning concrete prepared with short mixing times. Test results from both studies, however, demonstrated that concrete of adequate strength can be obtained from a mixing time as short as 20 seconds, excluding transfer time. Concrete of maximum strength obtained during the supplementary study was produced with a mixing time of 45 seconds. The increased strength ratios shown by tests for various mixing times on concrete from the Arkansas project are believed to have reflected the mechanical efficiency of the mixer used during the supplementary study.

It is noted that more concordant results were obtained from tests made during the previous study. Although no explanation has been determined for some of the varying test results obtained during this study, it is believed that the harshness of the concrete used on the Arkansas project caused some of the exaggeration of the differences in strength exhibited by some of the test results.

Introduction

DURING THE CONSTRUCTION season of 1958, a study of the production of portland cement concrete in 34-E dual-drum pavers was conducted by 13 State highway departments in cooperation with the Bureau of Public Roads. A summary of the findings from that study was published in PUBLIC ROADS in 1960.[2]

When the report on that study was prepared, it was realized that the number of test specimens prepared per variable in each study by the different State highway departments might have been insufficient to average out the uncontrollable variables such as weather and the physical condition of the operators as it might have affected their efficiency. It was believed that insufficient data had been obtained for short mixing times.

The Arkansas State Highway Department had planned to cooperate in the study but delays in the accomplishment of the grading and drainage of the selected project site prevented placement of the pavement in 1958. Subsequently, when the placement of pavement was programed in 1960, the Arkansas Department offered to conduct a supplementary study of the production of portland concrete with the 34-E dual-drum paver and thus provide data that could be checked against the findings obtained from the previous tests.

This study was made during construction of the Arkansas Project F-021-3(8) on a relocation of U.S. Route 67, between North Little Rock and Jacksonville. Construction equipment used included a Koehring 34-E dual-drum mixer built in 1958 and in excellent condition. Equipment in the paving train included a spreader and vibrator, a finisher, a longitudinal float, and a jointing machine. The concrete pavement was covered for 24 hours with wet burlap and then sprayed with a pigmented curing compound. An average of 1,500 feet of pavement, 24 feet wide and 9 inches thick, was placed per 10-hour day.

Concrete design

The concrete was designed in accordance with the Arkansas specifications. The mix contained 5¼ bags of cement per cubic yard and had a maximum water content of 5.5 gallons per bag. The slump was approximately 2 inches, and the air content was between 3 and 5 percent. The aggregates used were natural sand and crushed stone from a local commercial producer. The mix proportions were 94-186-428 by dry weight, which limited sand to only 30 percent of the total aggregate on a solid volume basis. Despite the harsh mix resulting from these mix proportions, a satisfactory finish of the pavement surface was obtained because the concrete was vibrated.

Conclusions

Results obtained from this supplementary study agree with those reported for the previous studies made in 1958, that concrete of adequate strength can be obtained from a mixing time of less than 60 seconds, even with a mixing time as short as 20 seconds. It is possible that the mechanical efficiency of the paver used to mix the concrete for this project permitted the attainment of better results for short mixing times than those obtained in the previous study.

For each mixing time used in this study, a considerable range in compressive strength of the concrete was noted from tests conducted on the groups of specimens collected from different batches of concrete mixture. Also, for each mixing time, the compressive strength of the concrete increased or decreased at reasonably constant rates for certain groups of tested specimens. It is possible that the harshness of the mix was responsible for the extreme strengths noted for some concrete specimens; but, from available data, no valid explanation can be determined for the progressive increase or decrease in strengths noted from tests made on successive batches of concrete.

Program of Study

The preparation of a large number of concrete test specimens for each variable of mixing

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[1] This article was presented at the 41st annual meeting of the Highway Research Board, Washington, D.C., January 1962.

[2] *A Study of 34-E Dual-Drum Pavers*, by D. O. Woolf, PUBLIC ROADS, vol. 31, No. 1, Apr. 1960, pp. 1-10

time was desired for this study. It was believed that more information could be obtained per man-hour by limiting the preparation of specimens to cylinders. Consequently, no beam specimens were prepared for use in this study, and no tests were made for flexural strength of the concrete.

The planned program included requirements for the following listed operations: Tests to be made on concrete prepared with mixing times of 20, 30, 45, and 60 seconds, exclusive of transfer time; use of only one overload, of 20 percent; preparation of 108 specimen cylinders from concrete of each mixing time; and completion of a suitable number of tests for consistency, air content, and unit weight. Because of the excessive rainfall that interrupted the study period (June 21–July 21, 1960), it was necessary to deviate from the planned program and only 72 specimens were prepared from concrete of some mixing times. However, all the specimens prepared for each batch were divided into two equal groups; half were used for tests made at 7 days of age and the other half were used for tests made at 28 days.

Sampling procedure

Test samples were taken from the last batch of concrete placed on the subgrade before the paver backed to place the top course. Batches were sampled every 20 to 30 minutes. These samples, approximately 2 to 3 cubic feet of concrete, were shoveled into a pan from five locations in the pile. The pan was carried to a truck, which took the pan to the sample preparation site established for each day's work.

It had been planned to test every sample for consistency by the Kelly ball penetration and slump measurement tests and for air content by the Chace meter; then six 6- by 12-inch cylinders were to be cast. The Kelly ball tests were made on the concrete, which had been placed on the subgrade from the test bucket load, and the other tests were made at the sample preparation site. Tests for unit weight and determinations of air content by a pressure meter were scheduled to be made on alternate batches. The concrete cylinders were cast in cardboard molds with metal bottoms, and the completed specimen cylinders were covered with 5 layers of wet burlap. On the following morning, the molds were stripped, the cylinders were marked and then stored in tanks of water. The cylinders were taken to the Arkansas State testing laboratory one day before the date of testing. They were capped with a sulfur compound for the compression tests.

Mixing procedure

Personnel from the Bureau of Public Roads timed the mixing for the test batches of concrete. The contractor usually used a mixing time of 50 seconds. Because of poor subgrade conditions outside the forms, however, the paver could not operate continuously at a fixed mixing time as the batch trucks could not always back to the skip, discharge, and clear the skip in the required period of time. Consequently, to assure the validity of the study, when samples were to be taken four consecutive batches were mixed for the specified length of time, and the samples were taken from the fourth batch. To obtain samples from concrete mixed for 20 seconds,

Table 1.—Summary of Arkansas project concrete production test data

Samples taken	Air temperature	Consistency		Air content		Unit weight	Average compressive strength at—	
		Kelly ball	Slump cone	Chace meter	Pressure meter		7 days	28 days
60-SECOND MIXING TIME								
June 21, 1960:	° F.	In.	In.	Pct.	Pct.	Lb./c.f.	P.s.i.	P.s.i.
2:45 p.m.	-----	-----	4.0	6.0	-----	-----	2,620	3,320
3:15 p.m.	-----	4.0	3.7	6.9	-----	141	2,610	3,180
4:00 p.m.	-----	1.5	2.5	4.7	3.8	-----	4,040	4,940
4:40 p.m.	-----	1.2	1.6	4.3	-----	148	4,110	4,990
July 20, 1960:								
9:00 a.m.	88	2.0	2.5	5.2	3.8	-----	3,440	4,150
9:25 a.m.	94	1.5	2.4	5.0	-----	148	3,220	4,210
9:45 a.m.	94	1.8	1.6	4.0	3.9	-----	3,590	4,370
10:15 a.m.	91	2.0	1.9	5.0	-----	146	3,400	4,260
10:35 a.m.	98	1.4	1.5	5.0	4.0	-----	3,730	4,760
11:00 a.m.	98	1.3	1.4	5.0	-----	-----	3,610	4,600
11:20 a.m.	92	1.0	1.9	4.0	-----	150	5,190	6,230
11:40 a.m.	89	1.2	2.2	4.0	3.8	-----	4,210	4,730
Averages	-----	1.7	2.3	5.0	3.9	147	3,650	4,480
45-SECOND MIXING TIME								
June 22, 1960:								
10:10 a.m.	98	2.0	-----	4.3	4.3	-----	3,680	4,500
10:55 a.m.	98	2.8	2.6	5.2	-----	144	3,190	3,950
11:30 a.m.	98	1.8	0.8	3.9	-----	-----	3,150	3,980
11:55 a.m.	99	2.8	3.8	6.0	4.9	-----	2,770	3,800
1:50 p.m.	-----	2.8	1.3	4.3	-----	-----	4,000	4,660
2:20 p.m.	99	2.0	1.5	5.6	-----	146	3,440	4,420
2:45 p.m.	98	1.1	1.5	3.5	3.8	-----	4,370	5,510
3:15 p.m.	98	1.9	0.3	4.7	-----	146	3,420	4,100
3:50 p.m.	-----	1.8	1.1	4.3	-----	-----	3,170	4,180
July 20, 1960:								
1:20 p.m.	85	1.5	2.5	4.7	5.2	-----	3,840	4,700
1:45 p.m.	85	0.6	1.0	-----	-----	149	3,810	5,780
2:00 p.m.	83	1.0	0.9	3.5	2.7	-----	3,930	5,410
2:20 p.m.	83	1.5	1.9	-----	-----	147	3,930	4,820
2:35 p.m.	82	2.0	2.6	2.7	3.2	-----	3,560	4,660
2:50 p.m.	83	2.2	2.4	-----	-----	148	2,940	4,140
3:10 p.m.	85	0.7	0.8	-----	-----	150	4,730	6,060
3:30 p.m.	83	2.0	3.0	-----	4.2	-----	2,720	3,470
Averages	-----	1.8	1.8	4.4	4.0	147	3,570	4,600
30-SECOND MIXING TIME								
June 23, 1960:								
10:35 a.m.	-----	1.6	2.5	4.7	5.1	-----	3,150	4,170
11:00 a.m.	-----	1.6	1.2	4.3	-----	145	3,150	4,200
11:35 a.m.	-----	0.9	0.9	4.3	-----	-----	4,270	5,680
11:55 a.m.	-----	1.3	1.7	4.3	3.9	-----	4,280	4,450
1:35 p.m.	-----	1.4	2.4	4.3	-----	146	3,380	4,160
2:10 p.m.	-----	2.2	2.5	4.3	-----	-----	3,480	4,600
2:45 p.m.	95	0.9	1.8	4.3	3.6	146	3,120	4,240
3:15 p.m.	96	2.0	2.5	4.3	-----	-----	2,620	3,440
3:35 p.m.	95	2.4	2.0	4.3	-----	-----	2,670	3,830
July 21, 1960:								
9:30 a.m.	92	1.2	2.0	6.4	4.8	-----	3,220	3,800
9:55 a.m.	95	1.8	1.6	6.4	-----	148	3,180	3,960
10:20 a.m.	94	1.4	1.5	6.0	3.3	-----	3,960	4,410
10:55 a.m.	96	0.5	0.9	4.3	-----	-----	4,260	5,120
11:10 a.m.	86	1.2	0.6	4.7	3.1	-----	4,480	5,600
11:40 a.m.	91	2.3	1.9	5.2	-----	145	3,540	4,170
Averages	-----	1.5	1.7	4.7	4.0	146	3,520	4,390
20-SECOND MIXING TIME								
June 24, 1960:								
9:45 a.m.	90	1.7	2.5	4.7	4.6	-----	2,840	3,700
10:15 a.m.	90	2.4	2.5	3.5	-----	146	2,990	4,160
10:40 a.m.	91	1.6	2.2	4.3	-----	-----	2,690	3,590
11:00 a.m.	86	1.6	2.2	3.9	4.4	-----	2,470	3,290
11:25 a.m.	89	0.5	0.6	3.9	-----	147	5,070	[1] 6,220
11:45 a.m.	78	2.0	3.4	4.3	4.3	-----	2,760	3,610
July 21, 1960:								
1:25 p.m.	89	1.5	2.6	4.3	3.7	-----	2,490	3,440
1:45 p.m.	86	1.5	2.0	5.6	3.8	-----	2,710	3,250
2:10 p.m.	84	1.3	2.1	5.3	-----	147	3,600	[1] 4,900
2:25 p.m.	81	1.0	1.7	3.9	-----	148	4,280	4,360
2:40 p.m.	80	1.4	2.5	3.9	3.8	-----	2,300	3,540
2:55 p.m.	78	2.2	1.5	3.1	-----	149	4,160	[1] 4,900
Averages	-----	1.6	2.2	4.2	4.0	147	3,200	[1] 4,100

[1] These averages include the "wild" values for individual specimens.

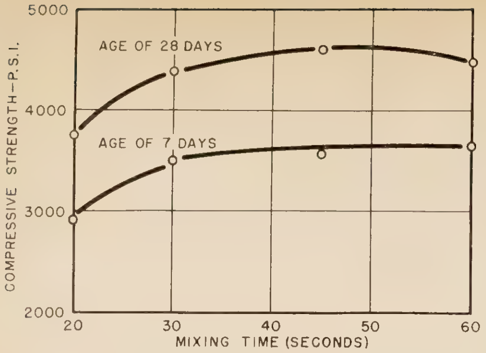

Figure 1.—Effect of mixing on compressive strength of concrete.

it was necessary to operate the paver manually and only one batch of concrete was mixed at a time. No appreciable difference in the appearance was observed for the concretes mixed for different lengths of time; the aggregate seemed to be well coated even in the concrete mixed for the shortest length of time, 20 seconds.

When this study had been about half completed, heavy rains and the resultant soil conditions halted construction on the project for a period of about three weeks. The study was subsequently completed without incident.

Although not pertinent to this study of concrete, it is of interest to note the plan devised by the contractor in an attempt to resume construction as soon as the weather had cleared. After the rain, the soil condition of the grade beside the forms was such that trucks could not be operated on it. To overcome this, the contractor tried double batching; that is, using two pavers, one on the service road and one on the grade. After a batch had been mixed dry in the first paver, it was dumped into the skip of the paver on the grade and, with the addition of water, mixed to form concrete. This procedure was conducted for only a few hours when the inspector closed the project because of spillage of materials.

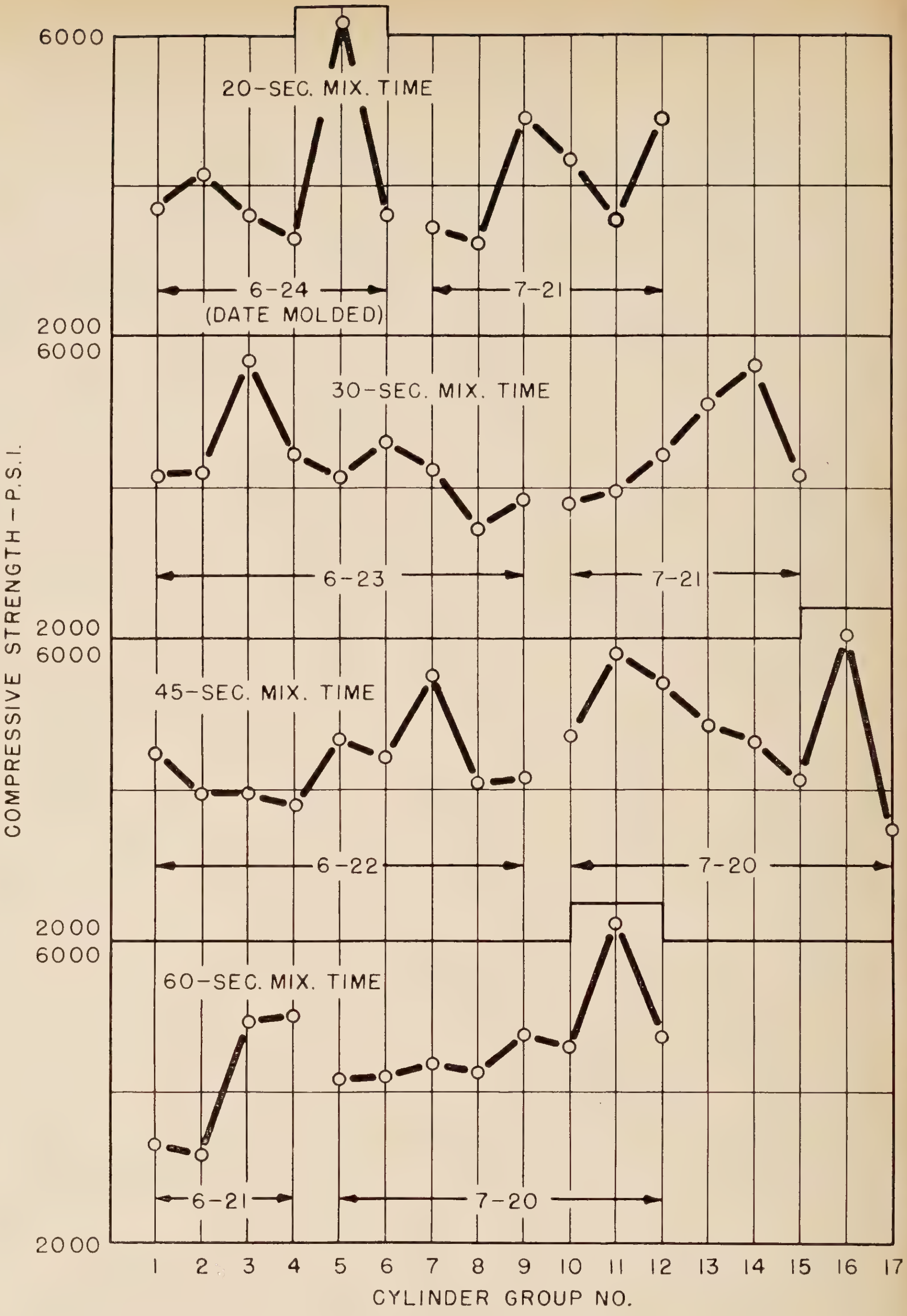

Figure 2.—Compressive strength of concrete at 28 days; groups of test cylinders arranged in chronological order of molding.

Effect of Mixing Time

Six cylinders were prepared from each batch of concrete tested. Compressive strength tests for the concrete were made on half of these cylinders at an age of 7 days and on the other half at an age of 28 days. Average values for the compressive strength determined for each group of three cylinders are given in table 1. Data are also shown on consistency, air content, and unit weight of the concrete.

The relation between mixing time and strength of the concrete is shown by the curves in figure 1.[3] Of the two curves, greater weight is given to the one representing results from tests made on specimens 28 days old. These curves show that the maximum strength of concrete tested in this study was obtained with a mixing time of 45 seconds. (All the mixing times shown exclude the transfer time.) With the results for the 60-second mixing time considered as unity, the strength ratios of the concrete for the various mixing times were:

Mixing time (seconds)	*Strength ratio (percent)*
60	100
45	103
30	98
20	[3] 84

The results shown for mixing times of less than 60 seconds are somewhat superior to those obtained in the preceding study. However, results from the tests of both studies demonstrate conclusively that mixing times as short as 30 seconds could be used with little reduction in compressive strength of concrete. The small differences shown by the two sets of test results probably reflect a difference in the mechanical efficiency of the mixers used.

Variations in Test Results

The compressive strengths of the concrete at 28 days, obtained from tests made on each

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[3] For the 20-second mixing time, compressive strengths of six cylinders were omitted because they were so unusually high as to appear questionable.

group of cylinders and arrayed chronologically, are shown in figure 2. Attention is called to some possibly unusual trends exhibited by the concrete specimens molded consecutively on the same day. For example, at 45 seconds of mixing time the specimens in groups 11–17, with one exception, had an almost uniform rate of loss of strength. The exception, the three specimens of group 16, had the highest compressive strength of any group of specimens tested in this series. However, specimens from group 17, the last of this series, had a low strength value which conformed to the general trend shown by groups 11–15.

For the other mixing times, similar progressive increases or decreases of compressive strength of the concrete specimens are shown in figure 2. For a mixing time of 20 seconds, two sets of three groups of specimens (2–4 and 9–11) had uniform decreases in strength. For a mixing time of 30 seconds, five groups of specimens (10–14) had a fairly uniform rate of increase in strength. For a mixing time of 60 seconds, no corresponding marked changes in strength were noted, although groups 5–12 had a slight but progressive increase in compressive strength with the exception of the specimens from group 11. The "wild" test results obtained from group 11 were similar to those obtained for certain single groups of specimens at each of the other mixing times, such as was noted for group 16 at 45-second mixing time.

Concrete strength test results

No definite relationship for all of the cases of progressive increase or decrease in compressive strength of the specimens tested at an age of 28 days can be shown by the data collected during this study. As will be discussed later, available data have been correlated with the results noted from tests of one of these cases. But for the other cases, some assumptions (which could be called guesses), have been made.

Most of the test results showing progressive increases or decreases in compressive strength of the concrete were obtained from specimens made in July 1960. All but one group of the specimens from the 60-second mixing time, which were molded during the morning of July 20, had increasing strengths. Specimens from the concrete with a 45-second mixing time were molded during the afternoon of July 20, and six of the eight groups of cylinders had progressively decreasing strengths.

The concrete specimens molded on the following day, July 21, showed a pattern of behavior similar to that obtained in tests on the specimens from the previous day's molding. The specimens molded in the morning were from the concrete with a 30-second mixing time and, with one exception, had progressively increasing strengths. Specimens from the concrete with a 20-second mixing time were molded in the afternoon and had varying strengths. Of the six groups of cylinders tested, specimens from three consecutive groups had steadily decreasing strengths, those from the first two groups of the series had lower strength values, and those from the last group had higher strength values.

Explanation of Unusual Test Results

To explain unusual results obtained from tests made on concrete during construction operations, writers frequently refer to items for which no determined values are available. The temptation to do that in this article is quite strong. Of all the various items that would have had a marked effect on the strength of the concrete but for which data are not available, the first choice is the water content of the fine aggregate. Normal variations could have been expected in this water content and might have caused the unusual test results. The receipt and use of a new lot of sand in a moist condition could have caused the strength of the concrete to decrease. Use of sand stockpiled and subjected to the high atmospheric temperatures that prevailed during much of the time of this study could have caused the strength of the concrete to increase. However, in either case any surplus or deficiency of water in the sand used should have been reflected in changes in the consistency of the concrete.

Tests on Concrete Batches

Figures 3 and 4 show the average values obtained from various tests performed on batches of concrete mixed for 20, 30, 45, and 60 seconds, respectively. For each mixing time, test data are presented that show average compressive strength, penetration determined by the Kelly ball method, slump measurement, and air content determined by the Chace meter. In several cases, air content data were not available.

Concrete, 20-second mixing time

The average test values obtained for concrete batches from the 20-second mixing time, shown in figure 3, do not provide a clue to the reason for the two series of progressively decreasing strengths. On the contrary, the test data obtained for consistency and air content of the concrete are in opposition to the trend of the results obtained from strength tests. Little basis for an explanation of the test performance of concrete from batches 2–4 and 9–11 is provided by these data. The high strength shown for batch 5 is reflected, however, by the decrease in consistency measured by the Kelly ball penetration and slump tests.

Concrete, 30-second mixing time

Information concerning the concrete produced with a 30-second mixing time is shown in figure 3. Tests showed the concrete from batches 3 and 14 to have high compressive strength and that from batch 8 to have the lowest strength of the 15 batches tested. Tests on concrete from batches 10–14 showed a set of progressively increasing strengths.

The records from slump tests of the concrete with a 30-second mixing time for batches 10–14 show a steady decrease in consistency, which could well be associated with the increase in strength recorded for these same concretes. The Kelly ball test results for these batches of concrete are irregular, as are the determinations for air content. It seems to be somewhat questionable that a change in slump from 2.0 inches to 0.6 inch could cause a change in compressive strength from 3,800 p.s.i. to 5,600 p.s.i. Possibly, it would be proper to consider these slump measurements as indications that a change in consistency occurred, which must have been accompanied by some other change that affected the compressive strength of the concrete and caused such a variation.

The high strengths shown by the tests on concrete from batches 3 and 14, and the low strength shown for concrete from batch 8, are associated with the low and high slump measurements, respectively. The results of the Kelly ball penetration tests showed the same degree of association with the strength of the concrete from various batches as those for the slump tests, but were not of similar magnitude.

Concrete, 45-second mixing time

Test data recorded in figure 4, for the concrete prepared with a 45-second mixing time, show that three batches of concrete had high or reasonably high strength values whereas one had a low value. With the exception of the highest strength value recorded, for batch 16, a progressive decrease in strength was noted for a series of seven batches of concrete (11–17). The first batch of this series, number 11, had a strength of 5,780 p.s.i. at 28 days and, except for batch 16, the strengths of the concretes of this series decreased almost uniformly to the 3,460 p.s.i. recorded for batch 17.

A progressive increase in penetration (a decrease in consistency) was shown by Kelly ball tests for the concrete from batches 11–15. However, the concrete of the 16th batch had only a small penetration value and that of the 17th batch was only slightly above the average for concrete in this series of batches.

The slump measurement for batch 17 was of some magnitude, but the slump measurements for batches 11–16 followed no definite pattern.

An insufficient number of Chace meter tests was made for the air content determinations of concrete in this series of batches to be of any assistance in explaining the progressive decrease in strength for this series.

Concrete, 60-second mixing time

Data from the tests on concrete prepared with a 60-second mixing time, as seen in figure 4, showed only a few correlations between strength and consistency or air content of the concrete from various batches. Concrete in batches 1 and 2 had relatively low values for strength and high values for consistency. Batch 2 concrete also had a high air content recorded by the Chace meter test. Batch 11 concrete had the highest strength, but the determinations for consistency or air content failed to show any reason for this. Concrete batches 5–10 in general showed an irregular but small increase in strength from 4,150 p.s.i. to 4,600 p.s.i. Similarly, a small decrease in slump measurement was noted for these same batches, but the Kelly ball and Chace air meter tests showed no trends in results similar to those obtained in tests for strength.

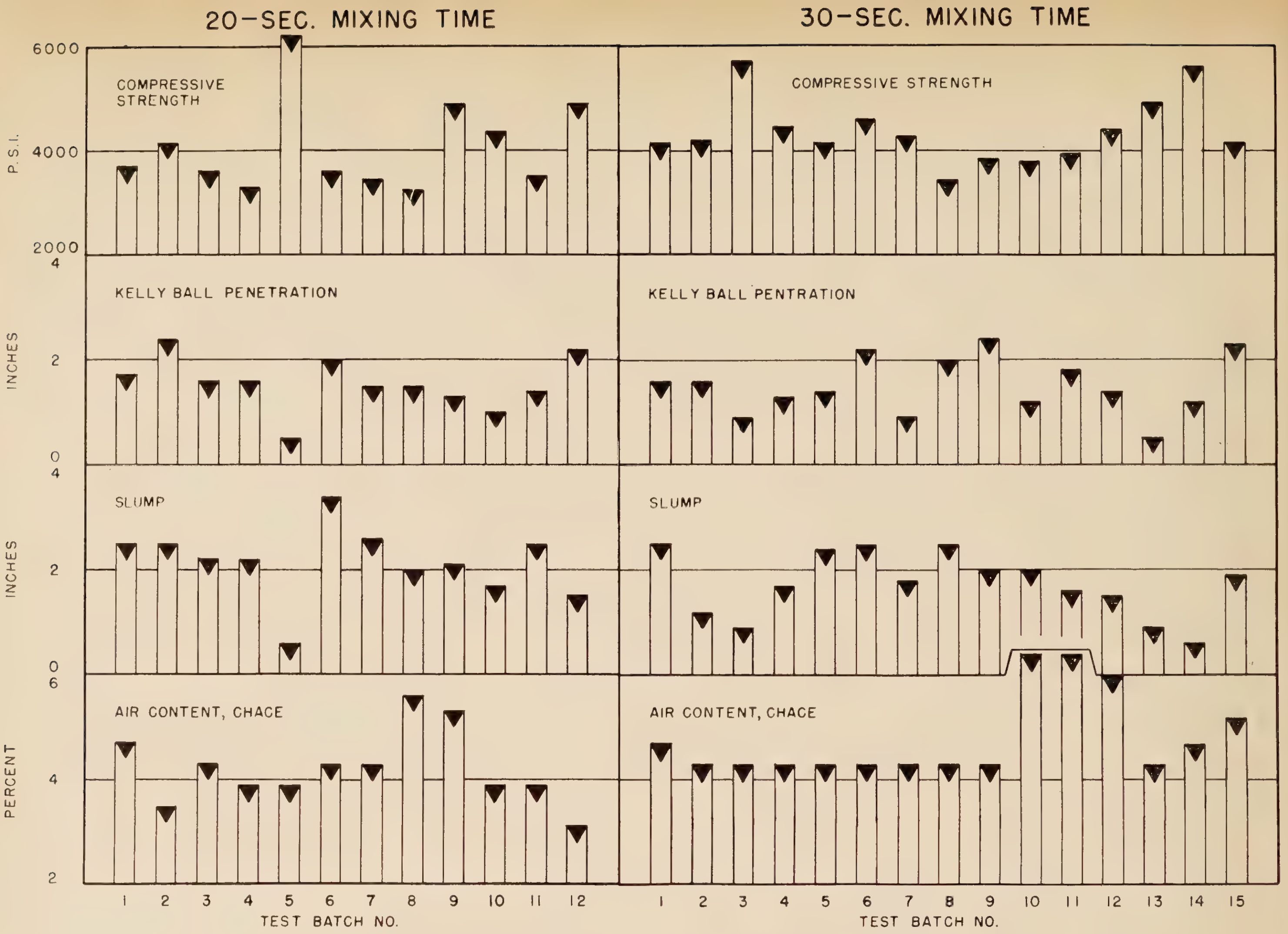

Figure 3.—Average values determined from various tests on batches of concrete mixed for 20 and 30 seconds.

Correlation of Test Results

In three out of four cases, more definite correlation was found between the test results for compressive strength of concrete and the slump measurement than between the test results for strength and either the Kelly ball penetration or the Chace air meter determinations. This was somewhat of a disappointment. It had been hoped that the Kelly ball and Chace meter test results would correlate closely with results of the strength tests of concrete. Because these tests for consistency and air content can be made quickly, it had been hoped that they could be established for use as acceptance tests with the definite knowledge of the close relationship of such test results with the strength of concrete. Such a relationship, however, was not established by test results of this study and the slump test remains the more reliable indication of the quality of concrete.

Chace Air Meter Test Results

Concretes of this study subjected to tests made with the Chace meter had an average air content value of 4.6 percent. This result is sufficiently different from the average air content value of 4.0 percent obtained from the tests made with the pressure meter to warrant caution in accepting test results obtained with the Chace meter. An air content of 4.0 percent is believed by many authorities to be about the lowest percentage of air that can be permitted and at the same time assure a concrete having adequate resistance to the effects of freezing and thawing. Increase in the air content to 4.6 percent should be accompanied by a marked increase in the durability of the concrete. Consequently, the results obtained in this study with the Chace meter indicate a durability for the concrete that may be misleading. As mentioned by others in reports on studies of the Chace meter, the test results obtained with this instrument should be considered to indicate general ranges in air content, i.e., high, medium, or low, and more precise indications should not be expected.

Control of Concrete Strength

In his paper on the probabilities of obtaining concrete of uniform strength, *How Good Is Good Enough*, presented at the February 1961 Convention of the American Concrete Institute,[4] Edward A. Abdun-Nur makes reference to the excellent Bureau of Reclamation control of the strength of concrete. Under this control, a coefficient of variation of practically 15 percent is obtained. In the analysis of the data for the Arkansas project, it was decided to determine the coefficient of variation for each group of data and to compare the values thus obtained with those for the mean deviation from the average. This latter step was taken because the mean deviation is considered less difficult to compute and is more readily understood. In addition, frequency distribution curves were prepared from the 28-day test results for the specimens representing each of the four mixing times.

The frequency distribution curves are shown in figure 5. The curve for the 20-second mixing time indicates that most values lie in a range of from 3,100 p.s.i. to 4,300 p.s.i. There were, however, some quite high test results, which caused a marked misshape of the curve and a shift upward in the average value. In the interests of reliability of the findings of these tests, it might be appropriate to classify the six highest test results for single cylinders as sufficiently "wild" to warrant

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[4] Journal of American Concrete Institute, vol. 59, No. 1, Jan. 1962, pp. 31-45.

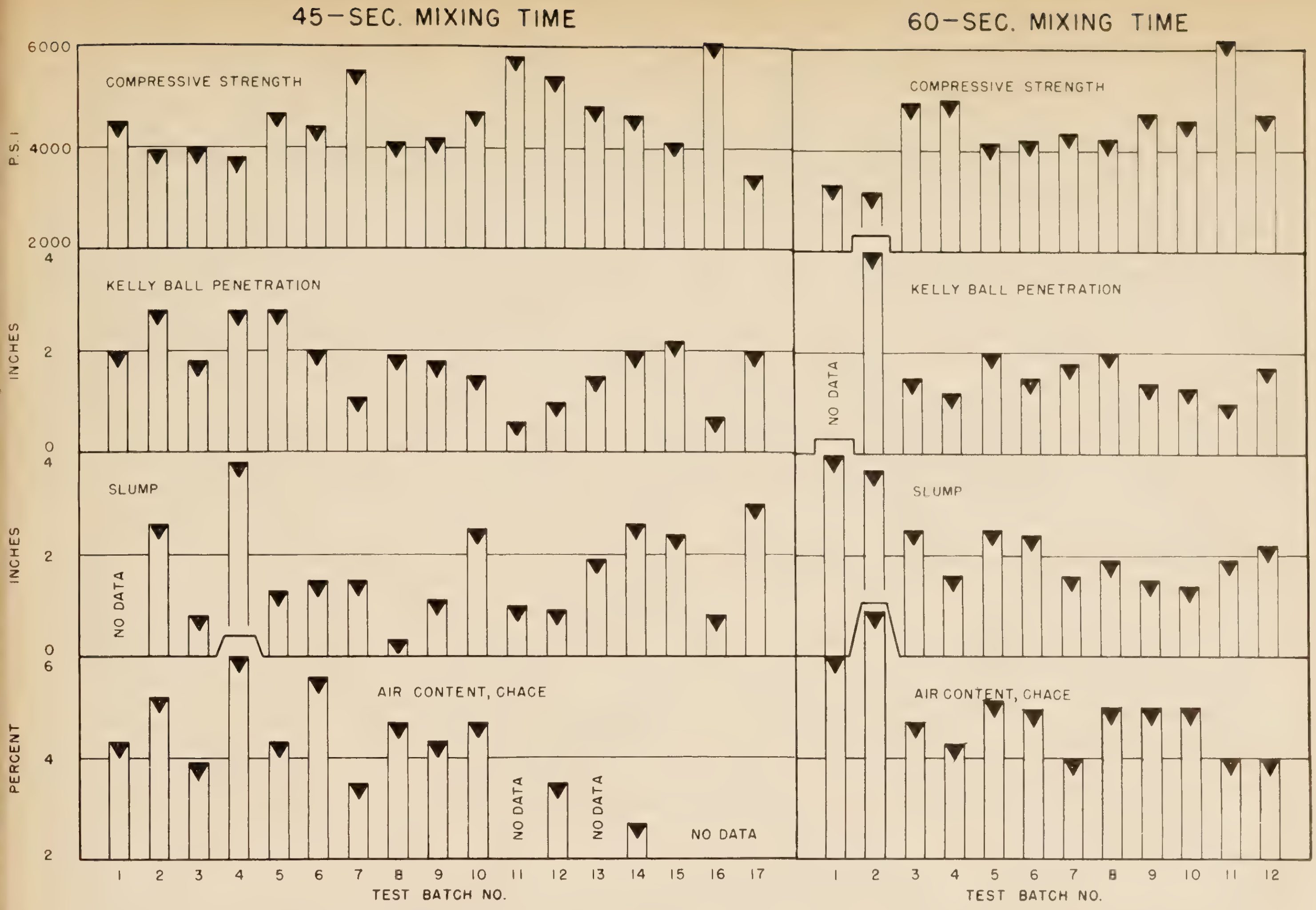

Figure 4.—Average values determined from various tests on batches of concrete mixed for 45 and 60 seconds.

their rejection from the data considered. If this were done, the average value for the remaining test values would become 3,750 p.s.i., a value more in keeping with the other findings of the study.

Although the curve for test data for concrete from the 45-second mixing time also shows a lopsidedness or skewness (as did that for the 20-second mixing time), the test data fail to show any particular point at which higher values might be considered "wild" or unreliable. Consequently, no adjustment of the average value has been attempted for these test data.

Values for coefficient of variation and mean deviation from the average are plotted in figure 6. The values determined by tests on concrete from the 20-second mixing time do not include the six "wild" results previously mentioned. Had these been included, the coefficient of variation would have been 21.8 percent, and the mean deviation from the average would have been 17.2 percent. For the values presented, it is interesting to note that the coefficients of variation are close to the 15 percent mentioned by Abdun-Nur as denoting excellent control of concrete strength.

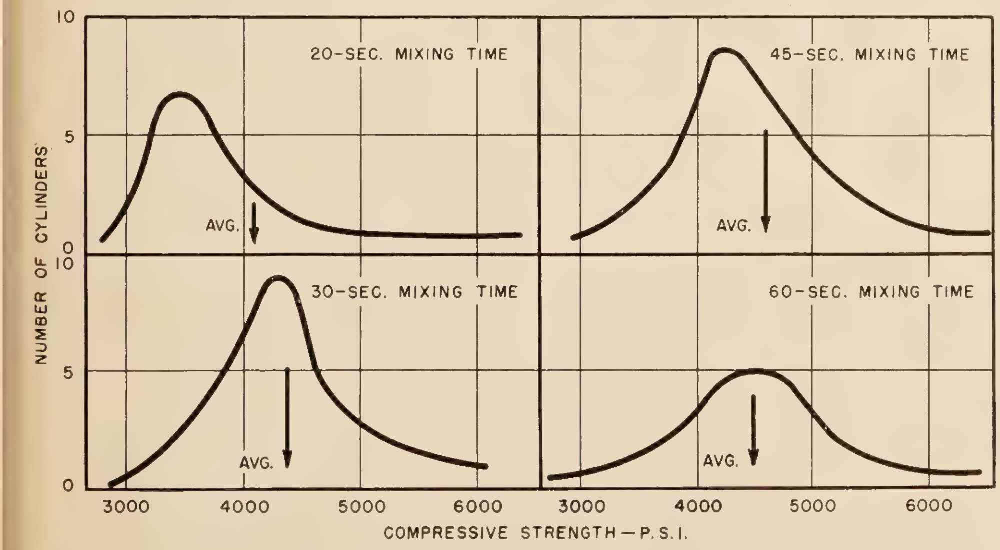

Figure 5.—Frequency distribution of compressive strengths of concrete at 28 days.

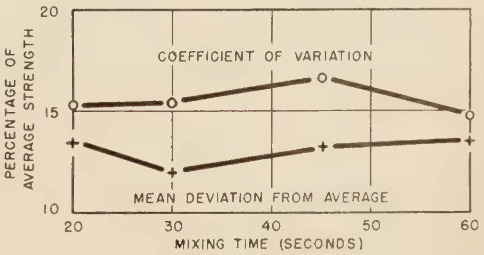

Figure 6.—Comparison expressions for uniformity of compressive strengths of concrete.

It is also noted that the mean deviation from the average follows closely the trend of the coefficient of variation.

On the basis of the frequency distribution curves shown in figure 5, the most concordant test results are shown to have been obtained with concrete mixed for 30 seconds. Some concern has been expressed about the nonuniform test results obtained during this study. As shown in figure 5, values markedly different from the average were obtained for some specimens prepared from concrete of each mixing time. The test data associated with the strengths of the concretes do not indicate why such variable results were obtained.

From a review of the data obtained in the 1958 studies for the different mixing times of the concrete, it was noted that the test results had generally been more concordant. Also, it was observed that when the concrete tested during the previous study had been described as harsh, there had been a tendency for a marked range in strength test results. It is believed that the harshness of the concrete used on the Arkansas project caused some exaggeration of the differences in strength normally found in tests of concrete made during construction. With a more plastic concrete, even lower values for coefficient of variation should be obtained than those reported here.

Arkansas Tests

In accordance with the requirements of their standard specifications, the Arkansas Highway Department drilled cores of the pavement for use in making determinations of the thickness of the slab and the compressive strength of the concrete. The compression tests were made on cores taken from the pavement at an age of 3 months. Results from tests on 59 cores showed the concrete to have an average strength of 4,430 p.s.i. with maximum and minimum strength values of 6,060 p.s.i. and 2,410 p.s.i., respectively. Strengths for the experimental sections of the pavement, determined from tests on the cores, are shown in table 2. These values do not agree with those determined in tests of the cylinders, but they do show that concrete of adequate strength was furnished even when mixing time was limited to 20 seconds.

Table 2.—Compressive strength of pavement determined from test cores

Mixing time	Number of specimens	Average compressive strength
Seconds		*P.s.i.*
20	2	3, 760
30	3	4, 180
45	4	4, 060
60	3	4, 530

Errata

In the December 1961 issue of PUBLIC ROADS, vol. 31, No. 11, a printer's error appears on page 222, in table 1, of the article, *A Laboratory-Field Study of Hot Asphaltic Concrete Wearing Course Mixtures.* The following words, which appear in the eighth and ninth lines of the first column of table 1: "has confusing appearance. Set [2]—" should be deleted.

Absolute Viscosity as a Specification Control for Bituminous Binders

BY THE DIVISION OF PHYSICAL RESEARCH
BUREAU OF PUBLIC ROADS

Reported [1] by J. YORK WELBORN, Chief,
Bituminous and Chemical Branch,
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Bituminous Materials and Chemical Section

The potential application of absolute viscosity as the basis for controlling the consistency of bituminous materials is of great interest to those concerned with the procurement and use of such materials. The historical development of present specifications, and the advantages to be gained by a change that would base specification requirements on kinematic values, are presented in this article. Problems related to the adoption of absolute viscosity as the control for both asphalt cements and liquid asphalts are pointed out—more complex problems are noted for asphalt cements.

A brief description is included of some of the instruments now available for determination of viscosity of each type of asphaltic material. Included in a related article appearing elsewhere in this magazine is a comparison of the Zeitfuchs cross-arm viscometer, for the determination of kinematic viscosity; and the Saybolt furol viscometer, now used for determination of furol viscosity.

Introduction

WHEN ASPHALT cement first came into use in the United States as a paving material, it was common practice for the engineer or chemist to determine its hardness by chewing a small portion of the material. It soon became evident to these pioneers that consistency was a very important property of bituminous material and, during the period between 1890 and 1910, the penetration test and other tests were devised to obtain more precise information about the relative consistency of bituminous materials.

Technology in nearly all fields of science and engineering has advanced at a tremendous pace since 1900, and the knowledge of highway materials possessed by engineers today is much greater than that of the pioneers. The highway engineer now uses consistency values to select a bituminous binder for a particular use and also as a basis for adjusting certain construction operations. The researcher has established the importance of consistency on the ultimate performance and durability of pavements. Despite such recognition of the importance of consistency of bituminous material, most of the standard tests being used today to measure this property are essentially the same as those developed by the pioneers.

Tests currently in use

There is little doubt that the tests now in use have done and are doing a creditable job; however, they have an inherent weakness in that they are empirical tests and measure consistency in a wide variety of units, which have only an indirect relation to viscosity. For example, the original consistency of liquid asphalt products is measured by the Saybolt furol viscometer in seconds, a unit of time. After distillation, the consistency of the residues of slow-curing materials is measured by the float test in units of time. The residues of the medium- and rapid-curing cutbacks are measured by penetration in units of length. The measurements of the Engler viscometer, used for testing consistency of tar products, are reported as the relation of the product's consistency to the viscosity of water; and the results of the softening point test used for both tar and semiasphaltic materials are reported in terms of temperature. Results obtained from all of these tests depend on the type of instrument used and the conditions of the test.

Because of the variety of tests and units of measurement, the highway and research engineers are hampered in relating data from one type of test with that obtained from another. Often, fundamental relationships involving viscosity cannot be determined because of the failure of the empirical consistency test to measure the viscosity accurately. Thus, the need for tests that will measure the consistency of all types of asphaltic or tar road materials in one basic unit is quite evident, and the logical choice for such a unit is the fundamental unit of viscosity.

While this idea is not new, having been suggested from time to time by a number of different writers almost from the very beginning of bituminous highway construction in the early 1900's, the move at the present time has more impetus and the backing of a greater segment of both research and testing organizations. The Highway Research Board's special committee on problems of mutual interest to consumers and producers of asphaltic materials has urged that studies be conducted and a concentrated effort be made to develop test methods and apparatus so that specifications can be based on viscosity in absolute units. The AASHO committee on materials is considering the problem, and research studies are being conducted by a number of State highway departments, the Asphalt Institute, individual producers of asphalt, and the Bureau of Public Roads.

Although the change to absolute viscosity as a specification control is clearly desirable from an academic standpoint, the fact that the empirical tests are an integral part of the highway engineer's thinking cannot be overlooked. Engineers understand the significance of results of the present tests and their differences in values; thus, it is important that the effect of any changes to absolute viscosity as the standard unit of measurement for asphalt consistency be considered carefully. The purpose of this article is twofold; namely, to

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[1] This article was presented at the 47th annual meeting of the American Association of State Highway Officials, Denver, Colo., Oct. 10, 1961.

consider in a general way the primary problems connected with specification control by means of absolute viscosity for both liquid asphaltic products and asphalt cements, and to review briefly the instrumentation that is available for determining viscosity for each type of material.

Brief Review of Basic Concepts

A brief review of the basic concepts involved and the definition of absolute viscosity are presented to point out some of the fundamental difficulties that must be overcome before specification control of consistency in terms of absolute viscosity units can be adopted for all types of bituminous materials.

Bituminous materials, being essentially viscous liquids, are extremely susceptible to viscosity changes as temperatures change. When expressed in absolute units, the viscosity of an asphalt cement at 32° F. is a billion times its viscosity at the mixing temperature (275° to 300° F.) of pavement materials. At the present time, no single instrument is available to measure viscosity over such a wide range.

The research technologist needs to define correctly the rheological properties (flow) of the bituminous material; to determine the manner in which these properties change with changes in temperature; to establish the relationship of the rheology of the bituminous binder to the characteristics and behavior shown by the paving mixture in the laboratory, during construction, and on the highway; and to prepare specifications that will control the important factors within the desired ranges. To produce deformation and flow, a force is necessary. Thus, in engineering terms, the primary interest of the technologist is in the stress/strain relationship of the viscous material.

When the stress/strain relationship is such that the strain (flow) is directly proportional to the stress, the material is a true (Newtonian) liquid. When the shearing stress of a Newtonian liquid is plotted against the flow produced by that stress, a straight line through the origin results. The numerical value of the slope of the line, when expressed in the proper units, is the coefficient of viscosity of the material, simply referred to as the viscosity. However, straight lines are not obtained for many viscous materials when the shearing stress is plotted against the rate of shear. The curve may bend upward, downward, or fail to pass through the origin. Various rheological terms are used to describe specific types of deviation from the straight line, but in this article such deviations are referred to as complex-flow or non-Newtonian properties of the bituminous material. Most asphalt cements will exhibit such complex-flow properties to some extent at atmospheric temperatures. The degree of complexity will vary for different materials.

Absolute viscosity

The unit of absolute viscosity is the poise. When a shearing stress of one dyne per square centimeter induces a unit rate of shear, the coefficient of viscosity is one poise. The unit rate of shear is obtained when two parallel planes of the liquid, one centimeter apart, have a velocity of one centimeter per second with relation to each other. The liquid in between the reference planes is considered to consist of innumerable parallel planes, each of which has a relative velocity that is proportional to its distance from the reference planes. It should be noted that the fundamental unit of the rate of shear in this usage is not centimeters per second as might be implied by the terminology used but is centimeters per second per centimeter, which reduces to 1/sec. This is usually referred to as seconds $^{-1}$ or reciprocal seconds.

Kinematic viscosity

Kinematic viscosity is often used instead of absolute viscosity, and its unit of measurement is stokes. This unit is the result obtained by dividing the absolute viscosity in poises by the density of the liquid under test. Kinematic viscosity is very useful for laboratory testing because it can be obtained directly without knowledge of the density of the liquid by measuring the flow of the material in a capillary tube. Measurements in both kinematic viscosity in stokes and absolute viscosity in poises, have been used in studies made with bituminous road materials. For asphalt cement, there is essentially no difference in the numerical value of viscosity, whether expressed in terms of poises or stokes, because the density for this material is close to 1 gram per cubic centimeter. In reporting absolute or kinematic viscosity, for convenience, the measurements are sometimes expressed in terms of centipoises or centistokes, which are one-hundredth of a poise or stoke, respectively. Also, the terms megapoise or megastoke are used to denote one million poises or stokes, respectively.

The problems relating to the application of fundamental units of measurement for absolute viscosity to the liquid asphalts are quite different from those relating to asphalt cements of the penetration grades; therefore, each type of material will be discussed separately.

The Problems With Respect to Liquid Asphalts

A survey of State specifications by the Bureau of Public Roads, in 1931, revealed a great difference of opinion as to what viscosity limits, types of viscometers, and test temperatures should be used to define the consistency of liquid asphaltic road materials being used at that time. This had resulted in numerous specifications and often had caused confusion in the production, control, and utilization of the products.

During 1932, the Asphalt Institute and the Bureau of Public Roads promoted and held a series of conferences with representatives of the State highway departments in an effort to simplify and standardize specifications for the rapid (RC), medium (MC), and slow (SC) curing asphaltic road materials. The outcome was the development of specifications for four grades of rapid curing and six grades of medium curing cutbacks, which were adopted by the Asphalt Institute in 1932, by the Federal Specification Board in 1933, and with minor revisions by the AASHO in 1938. Specifications for five grades of SC materials were also recommended and have been used by some agencies, but these have not been adopted by the AASHO.

These specifications represented a great improvement over the previous specifications by providing standards for systematic grading; however, uniformity was still lacking in the viscosity ranges specified for the various grades of different types of materials. Four temperatures: 77° F., 122° F., 140° F., and 180° F. were used when measuring the furol viscosity. It was found that when the viscosity limits were converted to one temperature, 140° F., the same number or grade designation did not indicate the same viscosity limits for SC, MC, and RC products, and the total range of viscosity was different for each type of material. Also, the gaps between consecutive grades were variable and, in two cases, the maximum viscosity of one grade of material was higher than the minimum viscosity of the material of the next heavier grade. These relations are shown in figure 1.

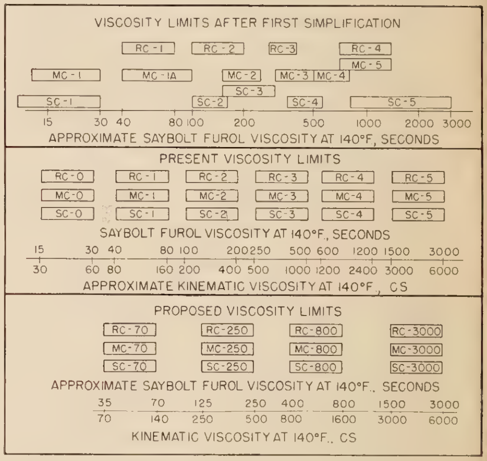

Figure 1.—Comparison of previous, present, and proposed viscosity limits.

Subsequent meetings were held by the Bureau of Public Roads and State highway departments to correct some of the deficiencies of the simplified specifications developed in 1932. The specifications in general use today were developed at these later meetings. These current specifications for MC and RC cutback were adopted by AASHO in 1942 and those for SC liquid asphalts were adopted in 1949. In these specifications, each type of liquid asphalt has been divided into six grades numbered 0 to 5, inclusive. The same viscosity range for a given grade has been established for SC, MC, and RC materials. The minimum and maximum limits of viscosity were selected so that each grade of material would be covered by approximately the same increment of viscosity at 140° F. when the viscosity was plotted on a logarithmic scale. The maximum viscosity permitted

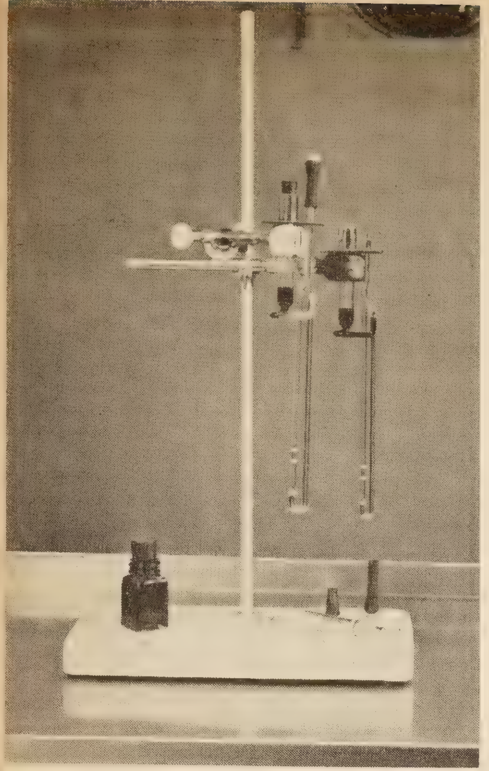

Figure 2.—Zeitfuchs cross-arm capillary viscometer.

for a given grade was specified at approximately twice the minimum viscosity permitted. Also, these revised specifications provided for a small but definite gap between the maximum viscosity permitted for one grade of material and the minimum viscosity established for the next heavier grade. The revised limits for viscosity are also shown in figure 1.

Although furol viscosity at 140° F. was used as the basis for establishing the limits of the various grades, actual tests could not be made at this temperature on all grades of material because of limitations of the furol instrument. For the most fluid grades of asphalt, flow from the furol viscometer is too fast at this temperature and inaccurate measurements are caused by turbulent flow; and for the heavy grades, flow is too slow at this temperature for accurate results. Thus, it was necessary to establish the approximate equivalents at other temperatures. Four temperatures varying from 77° F. to 180° F. were used to measure furol viscosity of the six standard grades of materials. A temperature of 210° F. has also been used for more viscous materials, such as the SC–6 grade specified by AASHO.

This limitation of instrumentation has now been overcome by the design of capillary tube instruments that measure the viscosity of opaque liquids, and by the availability of such viscometers in a range of capillary tube diameters. With these instruments the kinematic viscosity for all grades of liquid asphaltic materials can be determined rapidly, and with a high degree of precision, at 140° F.

Because a relatively precise conversion can be made from furol viscosity to kinematic viscosity, no fundamental problems are involved in changing the specification control of the liquid grades of asphaltic materials from furol seconds to the kinematic viscosity in centistokes. The kinematic viscosity in centistokes is very close to twice the furol viscosity, and one value can be easily converted to the other.

Several capillary tube instruments of various designs are available; all give satisfactory results, but the Zeitfuchs-type capillary appears to be the most popular. This tube is illustrated in figure 2. With this instrument the kinematic viscosity is determined by measuring the time of flow of the sample between the two calibration points on the tube. Viscosity is then a constant multiplied by the time. The constant for each tube is dependent on the diameter of the tube and volume between the calibration points, and is determined by calibration with a standard oil of known viscosity obtained from the National Bureau of Standards or the Cannon Instrument Co., State College, Pa.

An important step toward the practical application of kinematic viscosity to control the consistency of liquid asphalts was taken at the Fourth Pacific Coast Conference[2] on Asphalt Specifications held at San Francisco, Calif., May 10–11, 1961. This Conference adopted recommendations to: (1) Reduce the number of grades of each type of liquid asphalt from six to four, (2) realine the viscosity limits, and (3) express these limits in units of kinematic viscosity at 140° F. The Conference also recommended that the Saybolt furol method of test be retained as an alternate, with the results being converted to kinematic viscosity in centistokes. Figure 1 shows the viscosity limits for the four grades and a comparison of these limits with those of the present AASHO specifications. The grades are designated by type and the numerical lower limit of kinematic viscosity, such as SC–70, MC–70, RC–70, etc. These new specifications were effective January 1, 1962, in those States accepting the recommendations of the Conference.

The advantages to the materials and construction engineers resulting from adoption of these new specification controls can be briefly summarized, as follows: (1) All determinations made in the materials laboratory can be made from tests conducted at one temperature, 140° F., instead of the four or five temperatures now required; (2) experience has shown that time will be saved in testing; (3) tests can be made more economically because additional capillary viscosity tubes cost less than extra tubes for the furol viscometer; (4) better precision of test results can be expected; (5) the availability of results in fundamental units will permit a more scientific evaluation of the relation of consistency to the road behavior of these materials.

The Problems With Respect to Asphalt Cements

In the foregoing discussions, it was indicated that there were no serious problems and a number of advantages with respect to specifying kinematic limits for liquid asphaltic materials. However, the adoption of fundamental units to asphalt cements, with the complete elimination of the penetration test, presents very complex problems. These problems are: (1) Asphalt cements differ widely in viscosity-temperature susceptibility so that materials of equal viscosity at one temperature may have widely different viscosities at other temperatures. (2) Asphalt cements at atmospheric temperatures exhibit complex flow properties. The degree of complex flow differs for asphalts produced from different crude sources and by different methods of refining. (3) The degree of complex flow changes with temperature changes for individual asphalts; it also changes during hardening in service.

These same problems also apply to the application of absolute viscosity as a specification control for residues from the distillation of the cutback asphalts. The primary problems, nonuniformity and varying behavior in service of asphalt cements meeting the same specification, arise from the difference in viscosity-temperature susceptibility of different materials. It is well known that a group of asphalts, having identical penetrations and also identical viscosities at 77° F., can have widely different viscosities at high temperatures, such as those used for mixing. Viscosities at 140° F., the usual maximum for pavement temperatures, can also be significantly different. These differences are of considerable concern in a number of States, especially those in which a wide variety of types of asphalts are available. A number of suggestions have been made for minimizing the differences; such as placing minimum or minimum and maximum limits on the furol viscosity of the asphalt at 250° F. or 275° F. At present there also is considerable interest in the possibilities of basing the control of asphalt cement grade on the absolute viscosity at 140° F. Such control standards appear reasonable at first glance; but, a study of the possible variations under such conditions shows that specification control by viscosity at only one temperature, 140° F. may not be sufficient and could be even less desirable than the present standard for control at 77° F. by means of penetration.

Effects of change to control at 140° F.

Figure 3 was constructed to illustrate the possible effects of changing from control by penetration at 77° F. alone to viscosity measured at the single temperature of 140° F. The curves are approximations based on the assumption that the log of the log of viscosity in centipoises plotted against the log of absolute temperature in degrees Rankine (° F.+459.7) gives a straight line over the entire range of temperature from 20° to 350° F. Actual curves for asphalts generally show good

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[2] States included in the Pacific Coast Conference on Asphalt Specifications are: Arizona, California, Idaho, Montana, Nevada, Oregon, and Washington.

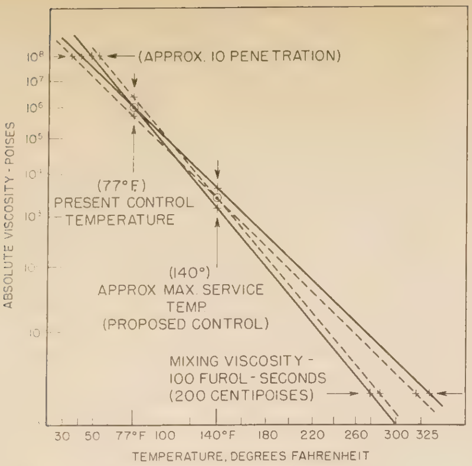

Figure 3.—Maximum and minimum viscosity-temperature relationships for 85–100 penetration grade asphalts.

conformity to this concept but there are indications that some materials deviate from a straight line because of unusually complex flow characteristics.

The slopes of the lines in figure 3 represent the extremes encountered with commercially available 85–100 penetration grade asphalts in the recent study made by the Bureau of Public Roads.[3] The solid lines are arbitrarily drawn to cross at 77° F. at a viscosity of 1 megapoise (one million poises), which is approximately equivalent to a penetration of 93. The figure 93 was calculated from a general relation between viscosity and penetration that was developed from actual tests made on a large number of asphalts in the Bureau of Public Roads laboratory. This relationship agrees closely with published relationships.

The dotted lines were obtained by bringing the curves together at 140° F. (the suggested point of control) in terms of viscosity. Table 1 shows the effect of maximum differences in viscosity-temperature susceptibility at several points of major interest. First, when control is based on penetration measured at 77° F., it is indicated that two materials having the same viscosity at 77° F. could have viscosities as low as 1,500 poises and as high as 4,000 poises at 140° F. The mixing temperature based on a viscosity of 100 furol seconds (200 centipoises or 2 poises) would be 273° F. for the material of high viscosity-temperature susceptibility, and 332° F. for the material with low viscosity-temperature susceptibility. There is no specific information that can be used to show precisely the point at which a pavement becomes brittle, but it is believed that a relative indication of this tendency can be obtained by considering the temperature at which the viscosity reaches a value of 100 megapoises, which is approximately equivalent to a penetration of 10. The range of temperature for the solid curves in figure 3 is from 41–48° F.

If the control is shifted to 140° F., as shown by the dotted lines, it becomes evident that differences in viscosity of the asphalt would be eliminated. Differences in temperature at the mixing viscosity would be reduced, the minimum temperature becoming 284° F. and the maximum 319° F. However, at a temperature of 77° F. or lower the possible variations encountered are much greater than might be expected. The curves show that the material most susceptible to temperature variations would have a viscosity of 2.3 megapoises, which is approximately equivalent to a penetration of 63; whereas, the material with the least susceptibility would have a viscosity of 0.5 megapoise, which is equivalent to a penetration of 132. The temperature range for 100 megapoises viscosity (approximately 10 penetration) would also increase; the new minimum would be 34° F. and the maximum 53° F.

The general curves in figure 3 are based on two materials having the same viscosity at the center of any given (or proposed) grade limits. However, actual variations could be considerably greater if the maximums and minimums of the asphalt grades were considered. These possibilities are shown by the values in table 1. It is of particular interest to note that, if viscosity limits at 140° F. of 1,500 to 3,000 poises were used as the limits for a particular grade, differences in penetration at 77° F. could range from a minimum of 48 to a maximum of 195. Although it may be possible to design pavements making use of materials with such different penetrations, it is obvious that some control is needed to prevent them from being supplied by the same specification.

Most asphalt technologists agree that it may be necessary to control consistency at two temperature points (or possibly three), thereby reducing the possibility of having materials with such differences meeting the requirements of the same specifications. At the present time, it is not possible to recommend what these points should be. However, from consideration of the various possibilities illustrated in figure 3 and table 1, it appears that one of the control points should be at 77° F. or lower.

Up to this point, only the problems related to the differences in viscosity-temperature susceptibility of the various asphalts have been discussed. It has been assumed that the deviations of paving asphalts from true liquids are not sufficiently different to affect specification control. This assumption is valid for values at 140° F. and above, but for values at lower temperatures, the complex flow characteristics of many materials would significantly affect the measured viscosity. The results of tests made at different shear rates give different apparent viscosities. To provide comparable data, it has become customary to report the apparent viscosity of all asphalt materials at a "standard" shear rate. Several rates or systems of reporting have been suggested for different viscosity ranges, but more information is needed as to which rate most nearly relates to the shearing forces in the pavement. Viscosity differences at different shear rates further emphasize the need to have at least one of the control points at a temperature appreciably below 140° F.

Instruments Available

It is important that instruments be available that will permit rapid and precise viscosity measurements in the laboratory. As mentioned earlier, the wide range of viscosity in asphaltic materials makes it impracticable to obtain results by using only one instrument. However, various instruments now available will permit coverage of most of the desired range.

One of the most popular viscometers used in asphalt research in the last few years has been the sliding plate microviscometer (fig. 4). This instrument, developed by the Shell Development Co., is useful for determining viscosities from approximately 100 thousand to 100 million poises. For asphalt cements, this represents a temperature range from a low of 40° to 50° F. up to a high of from 120° to 140° F., depending on the grade of material.

The test specimen for the sliding plate microviscometer is a "sandwich" of asphalt between two glass plates. In operation, one of the plates is held rigidly in the instrument and the other is attached to one part of a balance arm. A load is applied to the opposite end of the arm and the movement of the one plate with respect to the other is recorded. This provides data from which the rate of shear at various shearing stresses can be calculated. The apparent viscosity

Table 1.—Effect of differences in viscosity-temperature susceptibility for asphalts of same grade [1]

	Present control at 77° F.		Proposed control at 140° F.	
	Variation for equal values at center of grade	Total possible variation	Variation for equal values at center of grade	Total possible variation
Penetration at 77° F., 100 g., 5 seconds	[2] 93	[2] 85–100	63–132	48–195
Viscosity at 77° F. megapoises	[2] 1.0	0.88–1.25	0.50–2.30	0.22–4.0
Viscosity at 140° F. poises	1,500–4,000	1,300–5,500	[2] 2,300	[2] 1,500–3,000
Temperature range for 100 megapoise viscosity, (approximately 10 penetration) ° F.	41–48	38–50	34–53	30–57
Temperature range for 200 centipoise viscosity, (approximately 100 furol-seconds) ° F.	273–332	270–337	284–319	268–324

[1] Values shown are approximations based on general relationships and maximum and minimum susceptibility of asphalts produced in the United States.
[2] Control point.

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[3] *Properties of Highway Asphalts, Part I, 85–100 Penetration*, by J. Y. Welborn and W. J. Halstead, PUBLIC ROADS, vol. 30, No. 9, Aug. 1959, pp. 197–207.

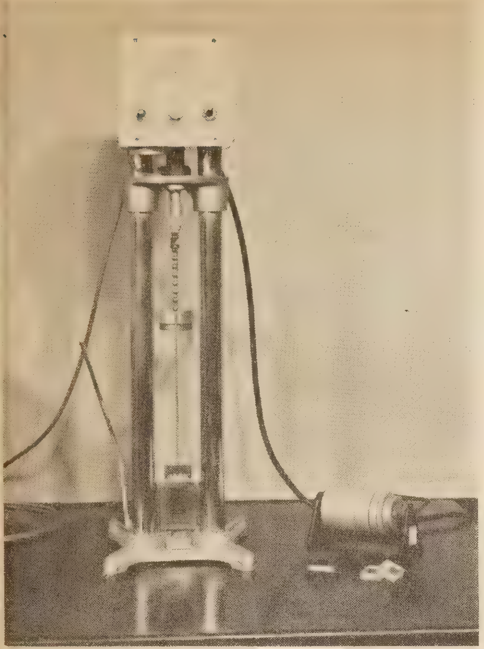

Figure 4.—Sliding plate viscometer.

at a predetermined "standard" shear rate is reported as the viscosity of the material. This instrument cannot be used to measure the viscosity of most asphalts at 140° F. because of the difficulty of holding the specimen in place and the extremely low shearing stresses involved. Several instruments, such as the rotating cylinder-type or the vacuum-operated capillary viscometer, are available that can be used to measure the viscosity of asphalts at this temperature.

At present, the greatest interest is being shown in the use of the vacuum-operated capillary-type of viscometer, which is illustrated in figure 5. With this device, the rate of rise of the liquid in a capillary tube is measured for specific values of vacuum applied at the top. The basic equation for capillary flow can then be used to calculate the absolute viscosity. Different sizes of capillaries, different heights of rise, and different amounts of vacuum can be employed to provide measurements over a relatively wide range of viscosities. Figure 5 shows the Koppers tube, which was developed some time ago; other designs of vacuum-operated capillary instruments, which employ the same principle of operation, also are now available.

A Zeitfuchs-type capillary instrument, previously discussed, is convenient to use for determining the viscosity of asphalt cements at high temperatures, such as those used for mixing. The furol instrument can also be used at these high temperatures and the results converted to kinematic units of viscosity.

With a combination use of the sliding plate, vacuum-operated capillary, and Zeitfuchs viscometers, the range of viscosities from 1 poise to 100 million poises can easily be covered, but these instruments cannot provide all the measurements considered desirable. Good instrumentation to measure viscosity at temperatures around 0° to 40° F., where viscosities are in the range of 1 billion to possibly 1,000 billion poises, is needed.

It is believed also that a concerted effort should be made to establish the relative importance of rheological differences in binders, such as shear susceptibility, age hardening, or gelling; these factors are not fully taken into account by the present practice of expressing viscosity at a "standard" shear rate. In particular, studies at low temperatures are needed to develop the relation of pavement brittleness to the properties of the binder. Instruments are also needed to measure apparent viscosities at such low temperatures. While the asphalt industry in general has shown, and continues to show, a very cooperative attitude with respect to such studies, the primary responsibility to establish overall relationships and to translate these relationships in terms of specification requirements rests with the various State highway departments. It is hoped that the States, through their own research and the cooperative research with the Bureau of Public Roads, will accept the challenge that these problems represent.

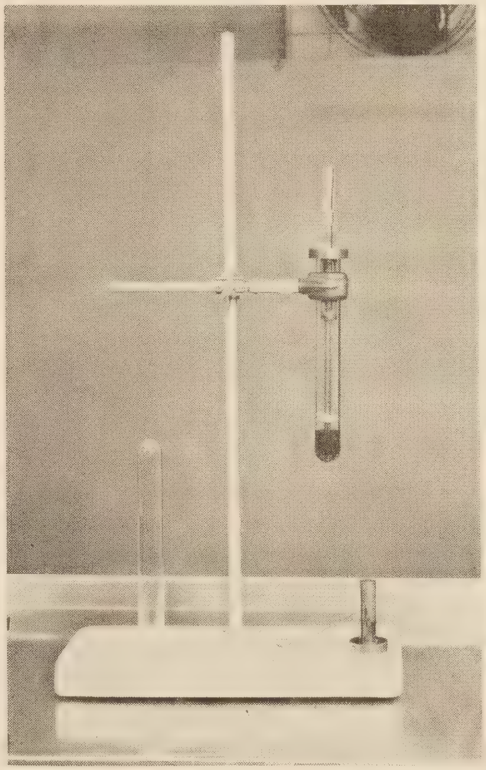

Figure 5.—Vacuum capillary viscometer.

Summary

To summarize, the problems relating to specification control of bituminous materials have been shown to be quite different with respect to the liquid asphaltic products and the asphalt cements. The present specifications for liquid asphaltic road materials are based on relationships of furol viscosity at 140° F. for all grades, and the changeover to specifications based on kinematic units at 140° F. could be accomplished easily because the furol viscosity can be converted to kinematic units with satisfactory accuracy. The primary advantages to such a changeover would be the convenience of being able to make all laboratory tests at the same temperature, and the resultant ready availability of the data in fundamental units, which would permit direct comparisons of different grades and types of liquid asphaltic materials.

It is very important that the rheological properties of asphalt cements be considered before viscosity limits based on temperatures other than those now used are established. It is recognized that the present empirical methods have shortcomings, and that studies should be continued toward the establishment of controls on the basis of viscosity tests. The use of fundamental consistency relationships should be introduced into pavement design and research studies. However, one-point control of viscosity, such as at 140° F., could possibly create greater differences with materials of the same grade than now exist with present grades and controls. Therefore, careful study of the effects of such a change and the possibility of establishing controls at two or more temperatures should be considered before viscosity units are adopted for grading asphalt cement.

Comparison of Zeitfuchs Cross-Arm and Saybolt Furol Viscometers for Measuring Viscosity of Cutback Asphalt

BY THE DIVISION OF PHYSICAL RESEARCH

BUREAU OF PUBLIC ROADS

Reported by EDWARD R. OGLIO and JOSEPH A. ZENEWITZ, Research Chemists, and WOODROW J. HALSTEAD, Head, Bituminous Materials and Chemical Section

The use of the Zeitfuchs cross-arm viscometer has recently been proposed for measuring the kinematic viscosity of cutback asphalt. This proposal is largely a result of the current trend toward measurement of the properties of bituminous materials by fundamental methods rather than by the customary empirical methods. The work reported in this article was undertaken to determine the feasibility of the instrument for this purpose.

A technique was developed for determining, with a high degree of precision, the kinematic viscosity of cutbacks with the Zeitfuchs viscometer. A comparison was made with the presently specified Saybolt furol viscometer. It was found that, with the new technique, significantly better precision was obtained with the Zeitfuchs viscometer than with the Saybolt furol instrument, and that the former was more convenient to use. The feasibility of using the proposed instrument for determining the viscosity of all grades of cutback at the same temperature was confirmed.

Introduction

CONSIDERABLE interest exists in a move to establish absolute viscosity as the standard for the measurement of consistency of bituminous materials. (See the article, *Absolute Viscosity as a Specification Control for Bituminous Binders,* appearing elsewhere in this magazine.) This interest has been generated by two factors—the trend toward measurement of fundamental properties of materials for the control of quality in production and research, and the present availability of practical instruments with which to make such measurements.

One of the various proposals that has been made in this area is that the Zeitfuchs cross-arm capillary viscometer be used to determine the kinematic viscosity of cutback asphalts and that kinematic viscosity be used as the measurement of consistency rather than, or as an alternate to, the presently specified Saybolt furol viscosity (*1*).[1] The Zeitfuchs cross-arm instrument is suitable for measuring viscosity of opaque liquids and, because of its availability in a variety of capillary diameters, it is also useful for making viscosity determinations at one temperature for all grades of cutback asphalts.

Although some State highway departments have used the Zeitfuchs viscometer to determine viscosity for both asphalt cements and cutback asphalts, the producers of asphalt probably have used it to a greater extent. The Phillips Petroleum Co. reports that it has used this instrument for a number of years to control the viscosity of its cutback products. This company has urged that kinematic viscosity be included as an alternate to the Saybolt furol viscosity requirement in current specifications for cutback asphalts (*2, 3*).

The comparison of the two viscometers reported in this article was made in an effort (1) to develop a technique for utilizing the Zeitfuchs cross-arm viscometer that might be suitable for inclusion in specifications, and (2) to obtain data for estimates of precision that can be expected when this instrument is used to measure viscosities of cutback asphaltic materials.

Conclusions

Results obtained from tests with both the Zeitfuchs cross-arm capillary viscometer and the Saybolt furol viscometer confirmed the feasibility of using the Zeitfuchs instrument for the determination of kinematic viscosity for all grades of cutback asphalt. This was specifically demonstrated by tests made at 140° F. with cutback asphalts of the present specification grade 5 and with the proposed specification grades of light (grade 70), light medium (grade 250), and heavy (grade 3,000) for both the rapid- and medium-curing types.

With the procedure developed during this study better precision for viscosity determinations of all grades of cutback asphalts may be expected with the Zeitfuchs viscometer than with the Saybolt furol viscometer. This procedure permits precise control of the volume of asphaltic material used in the test and the careful treatment of the asphalt sample, which are believed to be necessary for obtaining good repeatability of results.

Laboratory Tests

Three replicated determinations of viscosity on each of four grades of rapid curing (RC) and medium curing (MC) types of cutback asphalt were made in the laboratory with both the Zeitfuchs and Saybolt furol viscometers. The determinations with the Zeitfuchs tubes were made at a temperature of 140° F., in accordance with the ASTM method (*4*). The Saybolt furol determinations also were made in accordance with the applicable ASTM method (*5*), at temperatures appropriate for each grade. The samples were not filtered as specified in these test designations because they contained appreciable amounts of volatile thinner. The three determinations representing a replicated set were made simultaneously for the Saybolt furol viscosity tests and consecutively for the kinematic viscosity tests.

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[1] References indicated by italic numbers in parentheses are listed on page 251.

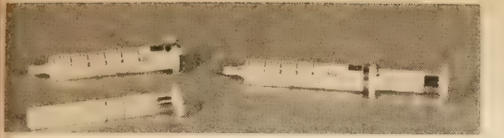

Figure 1.—Luer hypodermic syringe used to fill viscometer.

The test data were treated by the usual statistical procedures to determine the precision of results obtained for each instrument for each type of cutback.

Materials used in tests

The basic materials used in the preparation of the cutbacks for the comparison tests are described in the following list.

Grade 5 rapid curing cutback asphalt, with Saybolt furol viscosity of 327.6 seconds at 180° F.

Rapid curing cutback thinner (cutter stock).

Grade 5 medium curing cutback asphalt, with Saybolt furol viscosity of 408.6 seconds at 180° F.

Medium curing cutback thinner (cutter stock).

The base cutback asphalts were thinned with the proper volumes of the appropriate diluent to obtain materials within the viscosity ranges for the heavy (grade 3,000), light medium (grade 250), and the light (grade 70) grades of cutback materials proposed at the Fourth Pacific Coast Conference on Asphalt Specifications, May 1961. The Saybolt furol viscosities for these grades were approximately 300 seconds at 180° F., 200 seconds at 140° F., and 75 seconds at 122° F., respectively. All materials were stored in friction top cans and the determinations were made within one week after formulation of the test material.

Detailed testing procedure

The formulated test material was thoroughly stirred while at room temperature; care was taken to avoid incorporation of air. For the Saybolt furol tests, this thoroughly stirred material was poured into three furol tubes; for the kinematic viscosity tests with the Zeitfuchs viscometer, the material was poured into six 3-ounce, rubber-stoppered bottles. Six specimens were taken for the kinematic viscosity determination so as to permit a comparison for each material of the results obtained with Zeitfuchs viscometer tubes of two different viscosity ranges.

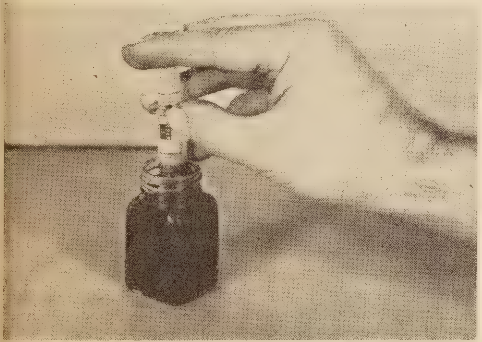

Figure 2.—Container for viscosity sample and illustration of technique for filling syringe.

In the Saybolt furol determinations, the viscometer bath and tubes had temperatures of from 0.5° to 1° F. above the test temperature when the samples were introduced into the tube. During the conditioning of the samples to test temperature, the tubes were kept covered and the contents were stirred continuously with the viscosity thermometers. From 20 to 25 minutes were required to obtain the test temperature. The three determinations constituting a replicated set were made simultaneously.

In the determination of kinematic viscosity with the Zeitfuchs tubes, a procedure was developed for the close control of the volume of the sample used in each replicated set of determinations. The necessity for controlling the volume of the sample had been indicated earlier, when the tubes were calibrated with the National Bureau of Standards (N.B.S.) standard viscosity oils to obtain the instrumental constants. During this calibration, in most cases, the filling line proved to be useless as a guide for introduction of the samples. With a number of tubes, the sample would spontaneously flow through the siphon and into the capillary. In addition, with the more viscous materials, such as the N.B.S. standard viscosity oils M, N, and P, it was practically impossible, by using the reference fill-line on the instrument, to control the volume of the sample for a determination. To accomplish this control and avoid having interfering droplets on the walls of the filling tube, a graduated Luer syringe was used to introduce the sample into the tube for tests made during this study.

The Luer syringe and its use in the filling of the viscometer are illustrated in figures 1–4. Because of photographic difficulties, only one hand is shown in these illustrations but two hands are required for some of the actual manipulations. The syringe, assembled and disassembled, is shown in figure 1. Special calibration markings were applied to the plunger. These calibration marks on the syringe's plunger were used in controlling the volume of the asphaltic material: the standard markings on the syringe are difficult to use with opaque materials. The type of container, and its relative size, used to hold the asphalt samples during conditioning and storage is shown in figure 2. The technique used to remove the air bubbles and adjust the volume of the sample in the syringe is illustrated in figure 3. In this procedure, material slightly in excess of that needed for the determination was drawn into the syringe, and the volume adjusted until the proper amount had been obtained; the extruded excess was removed from the syringe with paper toweling or cloth.

The viscometer and the syringe in place and ready for the filling operation are shown in figure 4. The test sample was discharged from the syringe at a slow steady rate by depressing the plunger with the forefinger. In this way, the rate of discharge easily was controlled to effect a quantitative transfer of the sample to the viscometer's reservoir without entrapment of air bubbles, which could have affected the results. Use of this technique also helped prevent the sample from touching or clinging to the upper walls of the reservoir and thus minimized the possibility of errors in results occurring from this source.

Figure 3.—Technique for adjustment of volume and elimination of air bubbles.

Efflux Time

Acceptable precision in efflux time was obtained with a material sample of 2.0 milliliters, for tubes applicable for viscosities of a range up to 3×10^3 centistokes; and with material samples of 3.0 milliliters, for tubes applicable for viscosities above 3×10^3 centistokes. These volumes, which corresponded to the volume of oil used in the calibration of the particular tube, were used for the kinematic viscosity determinations made during this study. The effect of the sample volume on efflux time obtained with the calibrating oils is shown by the figures in table 1.

Since a sufficient supply of Zeitfuchs viscometer tubes of any one particular range was not available, the replicated kinematic viscosity tests were made consecutively rather than concurrently as for the Saybolt furol determinations. The six 3-ounce, stoppered sample containers were immersed at staggered time intervals in a constant temperature bath held at 140° F., and allowed to condition for

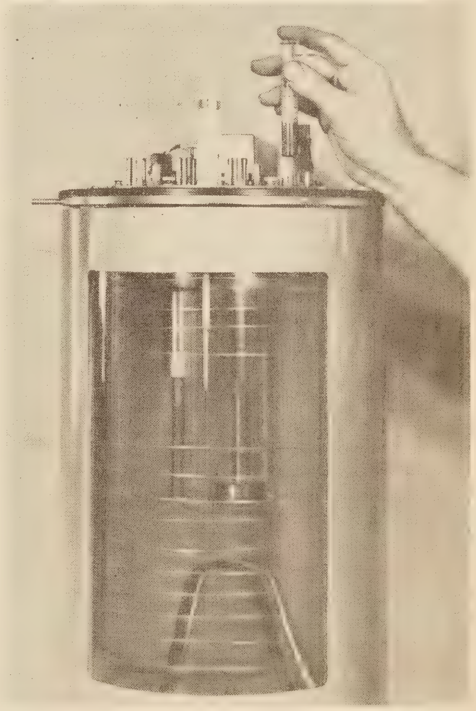

Figure 4.—Viscometer being filled from Luer syringe.

Table 1.—Effect of sample volume on efflux time with Zeitfuchs viscometers

Oil [1]	Temperature	Certification viscosity	Viscometer series	Volume of sample	Efflux time
	° *F.*	*Centistokes*	*Number*	*Milliliters*	*Seconds*
M	77	283.2	0.3	1.6 1.8 2.0	724.2 713.0 707.9
P	122	9,947.0	30.0	2.0 3.0	338.1 284.8

[1] N.B.S. standard viscosity oils, M and P.

Table 2.—Viscosity determinations and statistical summary

	Saybolt furol viscosity, seconds at—			Kinematic viscosity, at 140 ° F.—			
	122° F.	140° F.	180° F.	Viscometer[1] series	Centistokes	Viscometer[2] series	Centistokes
RAPID CURING CUT-BACKS:				*Number*		*Number*	
RC 5 grade	--------	--------	327.6	30.0	3,620.0 3,616.4 3,616.4	10.0	3,584.5 3,604.5 3,611.1
Average	--------	--------	--------	--------	3,617.6	--------	3,600.0
Standard deviation	--------	--------	--------	--------	2.1	--------	13.9
Coefficient of variation percent	--------	--------	--------	--------	0.06	--------	0.38
Light (grade 70)	83.7 84.5 83.6	--------	--------	1.0	110.25 110.06 111.15	0.3	109.91 110.07 111.54
Average	83.93	--------	--------	--------	110.49	--------	110.50
Standard deviation	0.49	--------	--------	--------	0.58	--------	0.90
Coefficient of variation percent	0.59	--------	--------	--------	0.53	--------	0.81
Light medium (grade 250)	--------	192.5 201.0 199.0	--------	3.0	408.75 412.30 410.36	1.0	407.73 407.91 409.00
Average	--------	197.50	--------	--------	410.47	--------	408.21
Standard deviation	--------	4.44	--------	--------	1.78	--------	0.69
Coefficient of variation percent	--------	2.25	--------	--------	0.43	--------	0.17
Heavy (grade 3,000)	--------	--------	305.2 308.5 315.4	30.0	3,181.1 3,170.5 3,230.2	10.0	3,189.7 3,209.7 3,221.9
Average	--------	--------	309.70	--------	3,193.9	--------	3,207.1
Standard deviation	--------	--------	5.20	--------	31.9	--------	16.3
Coefficient of variation percent	--------	--------	1.68	--------	1.00	--------	0.51
Pooled data coefficient of variation percent	2.01			0.69			
MEDIUM CURING CUT-BACKS:							
MC 5 grade	--------	--------	408.6	30.0	4,448.6 4,459.1 4,462.6	10.0	4,449.6 4,449.6 4,418.7
Average	--------	--------	--------	--------	4,456.8	--------	4,439.3
Standard deviation	--------	--------	--------	--------	7.3	--------	17.8
Coefficient of variation percent	--------	--------	--------	--------	0.16	--------	0.40
Light (grade 70)	86.0 87.0 85.0	--------	--------	1.0	110.97 110.61 111.33	0.3	110.91 111.35 110.91
Average	86.00	--------	--------	--------	110.97	--------	111.06
Standard deviation	1.00	--------	--------	--------	0.36	--------	0.25
Coefficient of variation percent	1.16	--------	--------	--------	0.32	--------	0.23
Light medium (grade 250)	--------	212.4 213.6 209.6	--------	3.0	444.29 444.94 445.26	1.0	443.15 444.23 443.67
Average	--------	211.87	--------	--------	444.83	--------	443.69
Standard deviation	--------	2.05	--------	--------	0.49	--------	0.54
Coefficient of variation percent	--------	0.97	--------	--------	0.11	--------	0.12
Heavy (grade 3,000)	--------	--------	290.0 287.0 291.6	30.0	2,956.4 2,991.5 2,956.4	10.0	2,947.9 2,977.9 2,974.6
Average	--------	--------	289.53	--------	2,968.1	--------	2,966.8
Standard deviation	--------	--------	2.34	--------	20.3	--------	16.5
Coefficient of variation percent	--------	--------	0.81	--------	0.68	--------	0.56
Pooled data coefficient of variation percent	0.96			0.58			
RC and MC pooled data coefficient of variation percent	1.58			0.63			

[1] Efflux time: Less than 200 seconds in each case.
[2] Efflux time: 200 seconds or more in each case.

20 to 25 minutes. After the conditioning period, the container was removed from the bath and unstoppered; the material was carefully stirred and about 0.5 milliliter more than the required volume was removed. This sample was taken by the Luer syringe, which had been preheated to about 125° F., from a level about 1 centimeter below the surface of the liquid. Any excess material or air, which might have been incorporated by the withdrawal procedure, was then expelled as previously described and the sample introduced into the reservoir of the viscometer and conditioned for 7 minutes in the constant temperature bath, as specified by the ASTM method (*4*).

Both the reservoir tube and the outlet tube of the viscometer were kept stoppered during the 7-minute conditioning period, to minimize evaporation and to prevent premature siphoning. The procedure from this point was in accordance with the ASTM test method (*4*). Individual stoppered containers were used to furnish material for each replicated determination, because an appreciable increase in viscosity occurred with each opening of the container for sample withdrawal. It was noted that prewarming was unnecessary when sampling the light grade material.

Table 2 contains the results for the replicated viscosity determinations, which were obtained with both the Saybolt furol and Zeitfuchs viscometers, for the various laboratory prepared grades of asphalt cutbacks and the current grade 5 cutbacks (MC and RC).

Statistical Treatment

The average and standard deviation were computed for each set of replicated determinations. For standard deviation, the computation was made in accordance with the recommendations for small sets of measurements found in most texts on statistical methods, as shown by the following formula:

$$\text{S.D.}=\sqrt{\frac{\Sigma(X-\bar{X})^2}{n-1}}$$

where,

X = an individual observation (a determination in the set).

$\bar{X}$ = the average for a set of three replicated determinations.

n = number of observations (3 for each set reported in this article).

In order to compare the precision of the results obtained with the Zeitfuchs instrument with those obtained with the Saybolt furol instrument, the coefficient of variation was also computed for each set. This is the ratio of standard deviation to the average expressed as a percentage:

$$\text{Coefficient of variation}=\frac{\text{S. D.}}{\bar{X}}\times 100$$

Standard deviation and the corresponding coefficient of variation were computed (table 2) for each type material and for each instrument. This was done in accordance with the following equations:

Pooled S. D.=

$$\sqrt{\frac{\Sigma(X_a-\overline{X}_a)^2+\text{- - - -}\Sigma(X_k-\overline{X}_k)^2}{(n_a-1)+\text{- - - -}(n_k-1)}}$$

Coefficient of variation=

$$\frac{\text{S. D. (pooled results)}}{\overline{\overline{X}}}\times 100$$

where,

$a_{--}k$=the replicated sets

$(n_a-1)+\text{- - - -}(n_k-1)$= sum of all the observations less one (for each set).

$\overline{\overline{X}}$=Overall average for the group of replicated sets considered (average of the averages for the group).

Summary

A comparison of the coefficients of variation of the pooled results for all the cutbacks, given in table 2, shows that the Zeitfuchs viscometer provided better precision than the Saybolt furol instrument. It is of interest to note that with the Zeitfuchs tubes no significant difference in precision was obtained between the types of cutbacks (RC or MC). With the Saybolt furol viscometer, appreciably better precision was obtained with the medium curing cutbacks than with the rapid curing type (0.96 percent vs. 2.01 percent). This difference is attributed to the lower volatility of the diluent in the medium curing materials, which resulted in smaller losses of these volatiles during sample preparation.

However, the precision of results obtained with both instruments for each type of the tested cutbacks was estimated to be less than that stated in the ASTM methods (*4*, *5*). This deficiency in precision is attributed to the volatile diluents in the cutback materials. This is confirmed by a consideration of the calibration data obtained with the three N.B.S. standard viscosity oils (table 3). With these oils, which contained no volatile diluents, the average deviation from the mean values of the efflux times was generally within the 0.1 percent level (*4*, *6*). Furthermore, the coefficients of variation computed for the replicated sets, as well as for the pooled data, were significantly lower for these oils than for the cutbacks. For the pooled data these coefficients were 0.13 percent for the oils (table 3) and 0.63 percent for the cutbacks (table 2).

Comparison of convenience

The Zeitfuchs tubes were somewhat easier to use and were more conveniently cleaned than the Saybolt furol tubes. The time required to complete a test was about the same for each instrument, 20 to 30 minutes. The conditioning time required for tests made with the Zeitfuchs viscometer was only 5 to 7 minutes, as compared to the 20- to 30-minute conditioning time required for the Saybolt furol tests. However, additional time was required for the preparation of material for the Zeitfuchs viscometer tests to obtain samples sufficiently fluid. For routine work with larger volumes of material, this additional preparation time could be considerably reduced by warming the sample on a hot plate. For kinematic viscosity determinations for the light grades of material (present grades 0–2) this prewarming step could probably be eliminated.

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Table 3.—Zeitfuchs precision data from N.B.S. standard viscosity oils

Oil	Temperature	Certified viscosity	Viscometer series	Volume of oil	Efflux time	Average [1] efflux time	Deviation from average	S.D.[1]	Coefficient [1] of variation
Type	*° F.*	*Centistokes*	*Number*	*Milliliters*	*Seconds*	*Seconds*	*Percent*	*Seconds*	*Percent*
M	77.0	283.2	0.3	2.0	708.05 708.8 707.55	708.13	0.01 0.09 0.08	0.603	0.08
M	77.0	283.2	1.0	2.0	156.8 156.6 156.65	156.68	0.08 0.05 0.02	0.104	.07
N	77.0	1,033.0	3.0	2.0	319.8 319.4 320.1 319.4	319.73	0.03 0.09 0.13 0.09	0.132	.04
N	68.0	1,515.0	10.0	3.0	135.75 135.15 136.1	136.00	0.18 0.11 0.07	0.219	.16
N	68.0	1,515.0	10.0	3.0	137.2 136.5 136.2	136.6	0.44 0.07 0.29	0.515	.38
P	122.0	9,947.0	30.0	3.0	283.6 283.1 283.1 283.4	283.3	0.11 0.07 0.07 0.04	0.245	.09

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[1] Pooled data showed: Average efflux time of 290.07 seconds, standard deviation of 0.375 seconds, and coefficient of variation of 0.13 percent.

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