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16. Abstract

During periods of wet weather, particularly when it is also cold, asphalt pavements develop potholes which cannot be immediately repaired with conventional asphalt materials. Materials are needed which can be successfully used to repair asphalt pavements in wet, or cold and wet, weather. The materials should be of reasonable cost and have at least a moderate life of one to three years.

This report is part of Research Study 359, "Rapid Repair of Wet Asphalt," funded by the Texas State Department of Highways and Public Transportation (TSDHPT) for the Center for Transportation Research at The University of Texas at Austin (CTR). The work described in this volume is a summary of the research done on fly ash as part of this study.

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Rapid Repair of Wet Asphalt

Research Project 3-18-83-359

conducted for

Texas
State Department of Highways and Public Transportation

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U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1985

PREFACE

This is the second in a series of reports which describe methods studied to repair potholes in asphalt concrete pavements during cold and wet weather.

The authors wish to thank the members of the Advisory Panel from the Texas State Department of Highways and Public Transportation: Larry Butler, Darren Hazlett, Gary Graham and Joe Duran. In particular, appreciation is given to Richard Tyler from D-10 Planning and Research whose suggestions and assistance in procurement of materials proved to be vital to the success of this project.

David Whitney, Dean Malkemus and James Stewart were instrumental in the laboratory and field investigations and their assistance is greatly appreciated. Special thanks are given to Michele Sewell and Jean Gehrke who prepared all the figures.

LIST OF REPORTS

Research Report 359-1, "Rapid Repair of Wet Asphalt Using Commercial Mixtures," by Brian Osterndorf, Alvin H. Meyer, and David W. Fowler. May 1985.

Research Report 359-2, "Rapid Repair of Wet Asphaltic Concrete Using Fly Ash," by David Cherem-Sacal, David A. Price, David W. Fowler, and Alvin H. Meyer. October 1985.

Research Report 359-3F, "Implementation Manual for the Rapid Repair of Wet Asphaltic Concrete," by David Cherem-Sacal, David A. Price, Brian Osterndorf, Alvin H. Meyer, and David W. Fowler. October 1985.

ABSTRACT

During periods of wet weather, particularly when it is also cold, asphalt pavements develop potholes which cannot be immediately repaired with conventional asphalt materials. Materials are needed which can be successfully used to repair asphalt pavements in wet, or cold and wet, weather. The materials should be of reasonable cost and have at least a moderate life of one to three years.

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SUMMARY

Most asphalt repair materials have been found to have difficulty making an adequate bond with wet asphalt, especially in cold weather. Various inorganic materials such as furan resin and magnesium phosphate are currently being considered for these kinds of repair. TSDHPT District 5 reports that Class C fly ash has been successfully used to repair potholes. The material hardens quickly and is said to be permanent. An additional characteristic which makes fly ash a desirable repair product is that it is very inexpensive compared with other materials now being tested.

This report begins by discussing the characteristics of fly ash as a material. Essentially fly ash is the finest part of the residue collected from fossil fuel power plants. Since the cementitious qualities of fly ash are highly dependent on the type of coal burned, various samples from different power plants were collected, tested in the laboratory and then in the field. After determining a desirable source for the fly ash, the focus of the project turned towards obtaining optimal ratios of sand, coarse aggregate, and water.

IMPLEMENTATION STATEMENT

This document presents an analysis of Class C fly ash as a potential pothole repair material in cold wet weather. All conclusions were based on laboratory and field tests. It is hoped that this report will be used in selecting an economical material for the repair of wet asphalt.

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CHAPTER 1

INTRODUCTION

Considerable research attention has been given in recent years to materials and methods for repairing portland cement concrete. However, relatively little attention has been expended on repair of asphalt cement concrete (ACC) pavements, especially in wet weather conditions.

Conventional rock asphalt and premix typically do not produce successful repairs in wet weather. The moisture present prevents adequate bond, and the repair life may be very short. Repair materials are needed which will have a moderate cost and a reasonable life. There are some rapid-setting materials used for repairing portland cement that have a good life expectancy but for an ACC pavement the cost of similar materials is often prohibitive.

A literature search was conducted to identify potential repair materials and methods. Only limited information on repair of asphalt pavements was found. However, there are some materials that appear to be promising candidates for repairing asphalt in wet weather. Reportedly, fly ash has been used successfully in Texas State Department of Highways and Public Transportation (SDHPT) District 5 to repair potholes. The fly ash is placed in potholes that are filled, or partially filled, with water. The material hardens quickly and is said to be permanent. Another inorganic material, similar to magnesium phosphate but less expensive, was developed as a rapid setting material for anchoring rock bolts in mines and is said to bond well to wet asphalt. No attempts have been made to use this material in the highway repair field. A third material, furan resin, which is a by-product of the cereal industry, is being used as a binder for aggregate. This material reportedly bonds well to asphalt and can be used with moisture present. Undoubtedly there are other materials which have a potential for repairing wet asphalt.

Several SDHPT districts have used cement-modified ACC as a patching material. Approximately 1-1/2 sacks of cement are added to each ton of limestone rock asphalt and mixed using a front end loader on site. Water is sprinkled over it to wet the cement, and the material is hand tamped into the hole.

Several manufacturers produce prepackaged asphaltic repair materials which are recommended for temporary repairs. Some of these materials contain RC 250, which produces faster curing; however, they are not recommended for wet conditions.

The SDHPT Materials and Tests Division has prepared a specification for an asphaltic material which is primarily for use in damp, wet weather. There are several commercially-available materials which are asphaltic mixes with a cutback. The rapid-setting materials, generally packaged in containers to prevent premature hardening, are usually quite expensive.

CHAPTER 2
FLY ASH AS A MATERIAL

2.1 Ash

Ash is the residue that is formed as a consequence of the imperfect combustion of matter. When ground coal is burnt, there are three types of residues: fly ash, bottom ash, and vapors.

Fly ash is the finest part of the residue and it is usually collected by air filters or by pollution control equipment. Section 2.2 will expand further on this component of the ash from coal, which is the topic of this research.

Bottom ash is composed of heavier and coarser particles than fly ash, which remain on the burning surface.

The vapors that are expelled into the atmosphere as a result of the combustion of coal are merely the volatilized portion of the various minerals contained in it.

2.2 Fly Ash

Fly ash, the lightweight spherically-shaped portion of the coal-combustion residue, is composed of 50 to 90 percent silica (glass). The major constituents of ash (silicon, aluminum, calcium, and iron) make up approximately 97 percent of its chemical composition. These elements form glass spheres of complex aluminates and silicates, calcium oxide, and iron oxide when they are exposed to temperatures of $2700^{\circ}F$ or more. This process occurs daily in the dozens of coal burning power plants around the world, generating millions of tons of fly ash. Up to 90 percent of the fly ash particles will pass a number 200 sieve, which indicates the importance of finding effective means of capturing and disposing of or using it. Once fly ash finds its way into the atmosphere, it can create serious environmental and ecological problems.

Whether the ash is distributed into fly ash or bottom ash depends on the type of burner, type of boiler bottom, and type of coal [3]. The particle size distributions of fly ash are a function of the type of collector employed. There are three types of tests to determine the particle size distribution: microscope count, turbidimeter, and hydrometer, and they all yield different results. The differences are ascribed to the varied specific gravities of the particles.

Fly ash is considered to be a pozzolan, which the American Society for Testing and Materials (ASTM) defines as: "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but which will in the finely divided form and the presence of moisture chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds possessing cementitious properties." Some fly ashes, in addition to showing pozzolanic activity, contain free lime in sufficient quantity to be cementitious in the presence of moisture. The type of coal from which the fly ash originated is the sole determinant of whether the fly ash is pozzolanic with free lime or plain pozzolanic.

ASTM classifies coals according to their respective caloric potentials. The most common for use in power plants are bituminous, sub-bituminous, and lignite. Bituminous coal is the highest in carbon content and is usually found in the central and eastern states. This type of coal has the highest efficiency in heat generation, and therefore yields the least amount of ash. Sub-bituminous and lignite coals are less efficient and, thus, produce more ash. These coals are considered to be less than prime grade and are usually obtained from strip mines in the west and southwest.

The ashes produced by the different types of coal present a chemical composition that is a reflection of the chemistry of their source. The fly ash from bituminous coal is relatively richer in aluminates, ferrites, and silicates and poorer in calcium oxide than its sub-bituminous and lignite counterparts. In contrast, the fly ashes of sub-bituminous and lignite coals are comparatively lower in aluminates, ferrites, and silicates and higher in calcium oxide. It follows from this explanation that the bituminous fly ashes exhibit pozzolanic behavior only, and the sub-bituminous and lignite fly ashes possess both cementitious and pozzolanic qualities, due to the presence of excess calcium oxide. From the caloric efficiency of the source, it is to be expected that the loss on ignition, a measure of unburned carbon particles, is markedly higher in bituminous ashes. Unburned carbon particles are not contributors to the strength of a mix.

The chemical composition of a fly ash affects its color; a light color indicates high calcium oxide and iron contents whereas a darker color signals increasing quantities of carbon.

ASTM classifies fly ashes as a function of their coal source: class F is for ashes of bituminous coal, and class C for ashes of sub-bituminous and lignite coals. Texas fly ashes are mostly class C, which has been less researched, since sub-bituminous and lignite coals have not been mined as extensively as bituminous ones. This research deals mainly with fly ash from Texas.

The Environmental Protection Agency (EPA), aware of the problems that the projected production of 1,500 million metric tons of fly ash in the United States for the year 2,000 will cause, has mandated the use of waste materials, such as fly ash, in government sponsored jobs. Due to the federal government's inducements and of fly ash, many ingenious ways of using it are being reported.

2.3 Uses of Fly Ash

2.3.1 Cenospheres

Cenospheres are hollow spheres 20 to 200 micrometers in diameter made of silicate glass and having a shell thickness of 10 percent of their radii. The hollow space within them is filled with gases, and thus the spheres are usually collected by letting them float, which also rids them of any soluble matter attached to their surface. The reasons why, conditions in which, and quantities in which they form are not very well documented, but up to 4 to 5 percent by weight or 15 to 20 percent of the volume of the fly ash has been reported to contain cenospheres. Their low density, inherent high-strength, and insulating properties have inspired their use in the following applications [1]:

1) in insulating cable tape and fabrics,
2) in acoustical paints, mastics and fillers,

3) as substitution for glass microspheres in the "syntactic foam" used for deep ocean buoyancy,
4) in the thermal protection system of the space shuttle orbiter,
5) in ceramic mufflers and combustion purifiers,
6) in lightweight floating portland cement concrete, and
7) in instant turf with an intact root system.

2.3.2 Other Applications

Fly ash has been used for many years as an additive, or partial substitute, for cement in portland cement concrete. The reasons for this are varied: the economic benefit of substituting fly ash for cement; the mitigation of the heat of hydration in massive concrete projects due to the slower rate of the pozzolanic activity, which dissipates the heat over a longer period and prevents thermal cracking; the achievement of higher long-term strengths; the improved workability, placeability, finishability, and pumpability, due to the regular sphericity of the fly ash particles; the ability to reduce the water content and add more coarse aggregate for the same slump, thereby increasing the strength; and reduced segregation and bleeding.

Another very well-known use is in the soil stabilization area, where the pozzolanic and cementitious properties are economically used to build strong and durable road beds.

Fly ash contains a myriad of trace elements in its chemical composition, which are used to nurture plants and fertilize soils.

Brick and paving tile containing 25 percent fly ash in lieu of clay are already being produced industrially. Besides the obvious economic advantage, the life of a good clay deposit is extended. This is particularly valuable for plants located in metropolitan areas.

Fly ash is an excellent fire retardant and has been successfully used to control and extinguish fires in mines.

Sand, water, and fly ash from Neyvelli, India, were tested for compressive strength in the late 1960s, but apparently were used only in combination with portland cement [4]. The 1980s have seen a practical revival of the use of this material, in the Baton Rouge, Louisiana, area by the State Department of Transportation and Development. A class C local fly ash was mixed with sand and coarse aggregates to patch pavement punchouts and breakouts. The patches have apparently performed very well [5]. In Texas, the State Department of Highways and Public Transportation (SDHPT) has used fly ash and water to repair potholes in District 5, with good results. There are no reports of prior laboratory research on the mechanical properties of fly ash and water mixes.

This report contains the procedures and results of the research done on the mechanical properties of fly ash mortar. Three Texas fly ashes were chosen for the investigations: 1) Deely from San Antonio, 2) Harrington from Amarillo, and 3) Welch from Cason. These fly ashes were selected for their relatively high calcium oxide content, which results in good cementing qualities. Since relatively little research has been done on class C fly ash as a total cement replacement, a large number of variables had to be considered in the development of this report. These variables include 1) ratio of dry ingredients, 2) sensitivity to water content, 3) temperature of ingredients, 4) pH of ingredients, 5) types of aggregate, 6) air temperature, 7) types of mixing, 8) variability of fly ash material, 9) possible additives to fly ash, and 10) different failure mechanisms. Because there is an excellent possibility that most of these variables interact with each other, care was taken to examine one variable at a time while holding the others constant.

CHAPTER 3
LABORATORY TEST PROCEDURES

3.1 Background

Six test procedures were performed on the three fly ashes that were formally researched; five were performed during the preliminary investigations. Four of the procedures follow ASTM guidelines, albeit modified somewhat, since the standard tests were designed for portland cement; the other two procedures are non-standard. Most of them were performed at 100^{o}F and 40^{o}F but all of them were also evaluated at room temperature, i.e., 72^{o}F. The 100^{o}F and 40^{o}F tests were evaluated with the temperatures of the ingredients, materials, and air all controlled in specially equipped environmental chambers.

The four ASTM test procedures were: (1) optimal curve determination, (2) cube compressive strength, (3) flexural strength, and (4) Gilmore needle set times. The two non-standard tests were: the calcium oxide content test by McKerall, Ledbetter, and Teague [2], and the peak exotherm test. The compressive strength and flexural strength specimens were removed from their molds when the material was set.

Four other tests were introduced later in the study as different ratios of fly ash, sand, and coarse aggregate were examined. Two of these new tests follow modified ASTM guidelines and two of them are non-standard.

The two additional ASTM procedures were: (1) static modulus of elasticity in compression and (2) compressive strength of concrete cylinders. The most important modifications were that 3-in. x 6-in.

cylindrical molds were used for both tests and that the contents of the specimens were vibrated instead of rodded. The two non-standard tests were: (1) DuPont test for plastic shrinkage and (2) shear strength of the fly ash/asphalt interface.

3.2 Compressive Strength

The cube compressive strength test was performed according to ASTM C109-80, "Compressive Strength of Hydraulic Cement Mortars." The specimens were cast in 2-in. x 2-in. x 2-in. (50.8-mm x 50.8-mm x 50.8-mm) steel molds and tested at 20 minutes, 30 minutes, 45 minutes, one hour, and one day for the preliminary research; and at approximately one hour, four hours, eight hours, 12 hours, one day, and one week for the formal investigations. The specimens were air-cured at the temperatures at which they were cast and removed from their molds as soon as the material was set. The universal testing machine was in a room with a temperature of 72°F.

The cylinder compressive strength test was performed according to ASTM C39-836, "Compressive Strength of Cylindrical Concrete Specimens." The specimens were cast in 3-in. x 6-in. (76.2-mm x 152.4-mm) cylindrical molds and normally tested at one day or one week. Vibration was used instead of rodding and again the specimens were air cured at 72°F before being tested on the universal testing machine.

3.3 Flexural Strength

The flexural strength test was performed according to ASTM C78-75, "Flexural Strength of Concrete." The specimens were cast in 2-in. x 2-in. x 12-in. (50.8-mm x 50.8-mm x 304.8-mm) steel molds. The beams were tested using third-point loading on a span of 6in. (152.4mm) at approximately one hour, four hours, eight hours, 12 hours, one day, and one week for the formal investigations; no flexural strength tests were done during the preliminary research. The specimens were air-cured at the temperatures at which they were cast and removed from their molds as soon as the material was set. The universal testing machine was located in a room with a temperature of 72°F.

The relationship between flexural stress and deflection was examined for some specimens using the apparatus shown in Fig. 3.1.

3.4 Gilmore Needle Set Times

The set times, i.e., initial set time and final set time, were determined in accordance with ASTM C266-77, "Time of Setting of Hydraulic Cement by Gilmore Needles." Three-in.-diameter x 0.50-in. thick (76.2-mm-diameter x 12.7-mm thick) pats were molded using an oiled acrylic ring, which yields reproducible results, rather than the specified handmade pats. The needles were lightly applied at several points until no visible mark was observed.

3.5 Optimal Water-to-Fly Ash Ratio

A graph of the one-hour compressive strengths versus water-to-fly-ash ratios was drawn to determine the optimum water-to-fly-ash ratio. The procedure to test the specimens to failure was the same as the one described in section 3.2. The selected water-to-fly-ash ratio was determined from the information gathered from the curve and from subjective judgment on workability and set times.

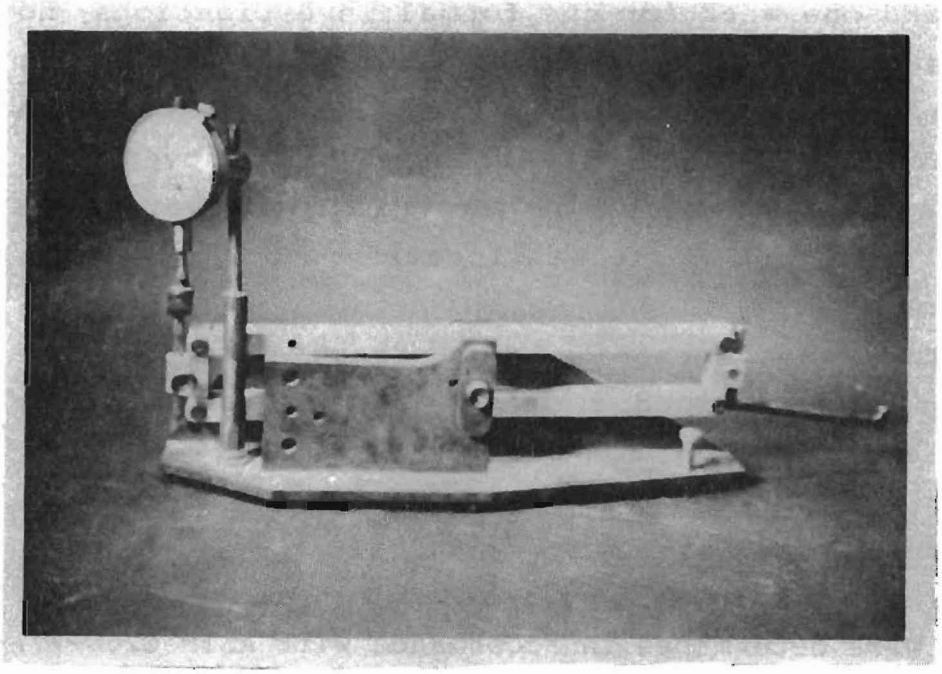


Fig. 3.1 Deflectometer used in all Load Deflection Tests to ascertain the relationship of peak exotherms to set times.

3.6 Peak Exotherm

The peak exotherm was recorded with a digital thermometer whose thermocouple was placed at the center of the mix in a 2-in. x 2-in. x 2-in. (50.8-mm x 50.8-mm x 50.8-mm) steel mold. The purpose of this test was to ascertain the relationship of peak exotherms to set times.

3.7 Calcium Oxide Content

As discussed in section 2.2, calcium oxide is responsible for the cementitious properties of fly ash; therefore, it is important to know its content. McKerall, Ledbetter, and Teague [2] developed a test based on the isothermic reaction that occurs when fly ash and hydrochloric acid are mixed together. The seven-stage procedure, as taken from reference 2, is as follows:

1) Allow the separated fly ash, the acid and a thermos bottle each to reach an equal and constant temperature (usually room temperature) and record the temperature (initial temperature).
2) Weigh out 20 grams ± 0.2 grams of fly ash and place it in the bottom of the thermos bottle.
3) Add 75 ml of 15 percent HCl to the fly ash in the thermos bottle and stir to insure mixing. (Fifteen percent HCl is made by mixing 6 parts of distilled water and 4 parts of 12 molar HCl (37.5 percent pure)).
4) Quickly cover the thermos bottle with the stopper and insert the thermometer, being sure the tip of the thermometer is touching the bottom of the bottle.

5) Observe and record the thermometer readings until a drop in temperature is seen (usually within 5 minutes).
6) Subtract the highest temperature observed from the original temperature found in Step 1. This will give the change in temperature in ^{o}C.
7) Calculate the total CaO content by use of the following formula:

$$CaO = 0.395\ (\ T) + 3.234$$

Where

T = change in temperature in ^{O}C found in Step 6.

CaO = total CaO content (recorded to nearest 0.1 percent).

3.8 Compression Modulus of Elasticity

The compression modulus of elasticity test was performed according to ASTM C469-65, "Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." The determination of Poisson's ratio is an optional part of this test and was not performed. The specimens were cast in 3-in. x 6-in. cardboard molds, vibrated instead of rodded, and cured at room temperature for one week. Vibration was used in place of rodding because of the speed at which fly ash tends to harden. A photograph of the compressometer used in these tests is shown in Fig. 3.2. A constant stress machine was used to apply the load at a rate of 15,000 lb/min. (114 Newtons/sec.)

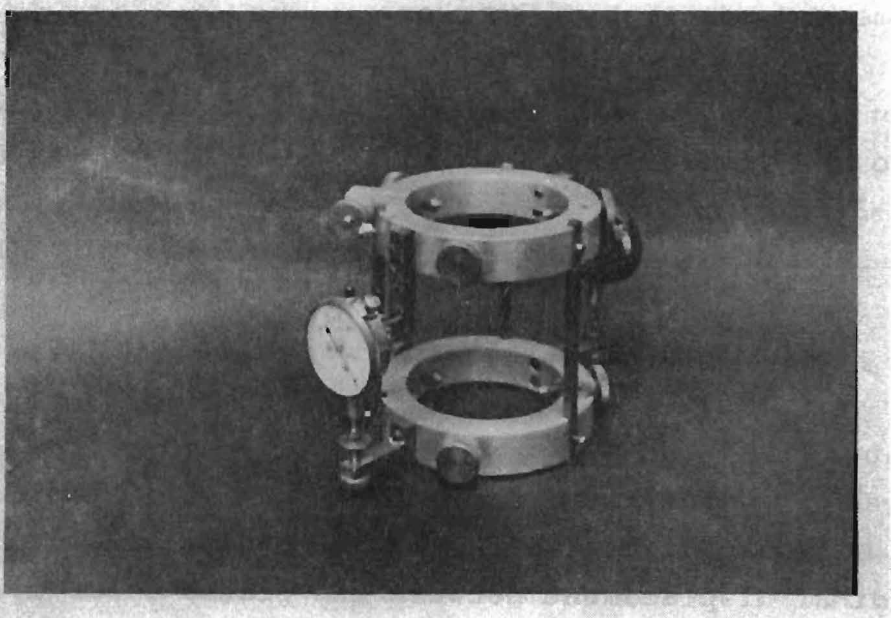


Fig. 3.2 Compressometer used in all Elasticity in Compression tests. Both gages are accurate to 0.0001 in.

3.9 Plastic Shrinkage

The plastic shrinkage strains for various fly ash mortars were measured as a function of time using the DuPont method of plastic shrinkage.

This method used a 3-in. x 3-in. x 12-in. beam specimen which was cast inside a Teflon -lined mold in order to reduce friction and to aid in specimen removal. Figure 3.3 shows a schematic of the testing device employed. A thin rod was supported at each end by a ball bearing support. Attached to this were two angle sections with a gage length of 10 in. between them. One angle section was fixed by means of a plate to the rod. The other angle section was attached to a plate on rollers which was only temporarily fixed to the rod by means of a pin. A DCDT was fixed to the rod in order to monitor the longitudinal displacement between the plates after the pin was removed from the free plate and allowed to move. The readings from the DCDT were then recorded on a chart recorder which allowed for variable speed control based on time.

Two specimens of each mortar were tested by this method. The fly ash mortar was mixed, placed into the mold, and properly rodded. The shrinkage measurement device was then inserted. The mold sides were tapped with a hammer to cause the mortar to surround the angles completely and evenly. The plate with the rolling capability was then unpinned, allowing it to move freely, and the system was zeroed. The set-up procedure took five to seven minutes from the time the mortar was placed. The test was run for 28 hours. The time to peak exotherm was also monitored for each sample, using a thermocouple.

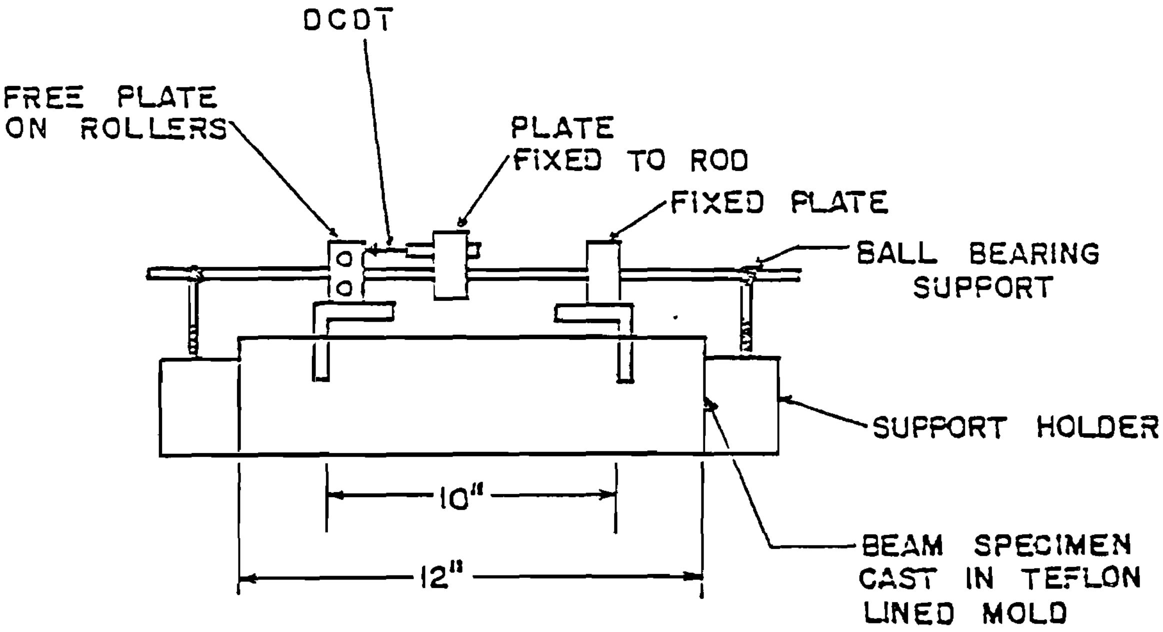


Fig. 3.3 Device Used to Measure Length Change in DuPont Method of Plastic Shrinkage Test.

Figure 3.4 shows the pin being removed from the free plate assembly.

3.10 Shear Strength at Interface

Any repair material must develop a certain amount of bond to the surrounding pavement into which it is cast. It would be extremely difficult to examine the exact nature of this bond since there is no current method to predict the contribution made by mechanical interlocking, nor the effect of unknown chemicals which may collect on the interface before the repair is made. In the laboratory, however, it is possible to make valuable comparisons of different mortars while keeping certain other variables controlled. This test shows the shear stress which can be developed at the interface between fly ash mortar and asphalt when the asphalt is relatively smooth and clean.

The testing apparatus consists of an ordinary 0.25-in. (0.64-cm) eyebolt, two nuts, and a piece of 0.125-in. (0.32-cm) steel plate. The eyebolt is welded to prevent the eyelet from opening and the steel plate is machined to a 2-in. (5-cm) outside diameter with a 0.25-in (0.64-cm) hole at the center. These pieces are then assembled together into what will be referred to as the pulling mechanism (Fig. 3.5). Note that there is a nut above and below the steel plate securing it in position. Also shown in Fig. 3.5 is a cylindrical specimen of hot-mix asphalt concrete approximately 2.5 in. (6.3 cm) high and four in. (10 cm) in diameter. This specimen was drilled with a 2-in. rock drill, leaving a cavity two in. in diameter and 1-1/8 in. (2.86 cm) deep. A smaller hole

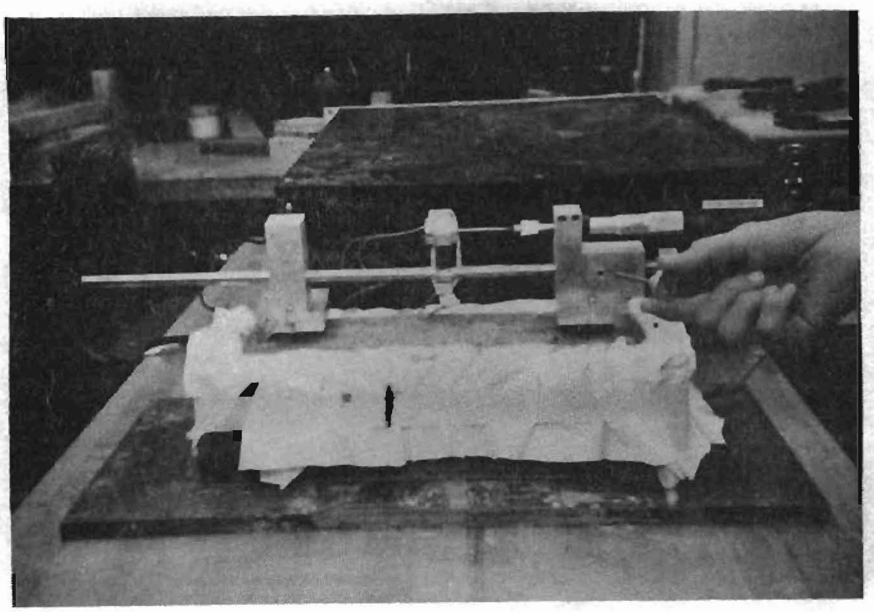


Fig. 3.4 Removal of pin from the free plate assembly initiates the beginning of the shrinkage test.

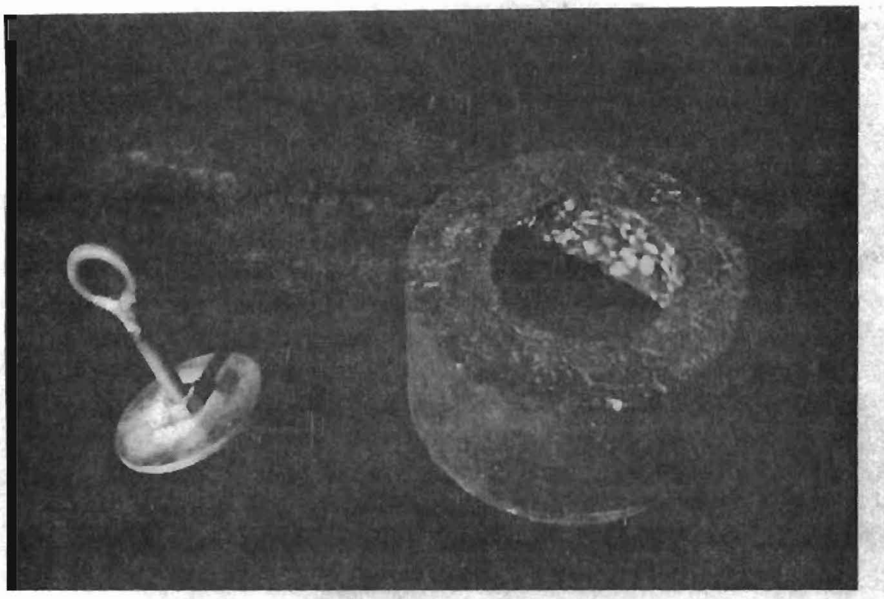


Fig. 3.5 Pulling mechanism and asphalt cylinder before testing.

was drilled at the base of the cavity to allow room for the nut underneath the steel plate of the pulling mechanism. The pulling mechanism should be placed within the cavity to check for proper seating and for free movement in and out of the cavity.

Test specimens were prepared according to the following procedure:

1) Brush the inside of the cavity and rinse it with distilled water.
2) Insert the pulling mechanism while the cavity walls are still wet.
3) Fill the cavity with fly ash mortar and screed off the excess. (Fig. 3.6)
4) Let the mortar harden for two hours.
5) Place a metal band completely around the asphalt specimen. Place plumber's tape around the metal band and finger tighten. The metal band prevents the asphalt from expanding while the finger tightening ensures that the asphalt is not in compression during the test.
6) Apply a tensile force through a cable to the eyelet and measure the force acquired to remove the pulling mechanism. (Fig. 3.7)

Three asphalt specimens were used for each of the fly ash mortars so that the variability of the tests could be determined. Because the steel plate prevents the mortar from adhering to the bottom of the cavity, the load at failure is directly proportional to the resisting shear stress at the interface. This stress is found by dividing the load at failure by the contact area of the cavity.

Fig. 3.6 Specimen prepared for shear strength test.

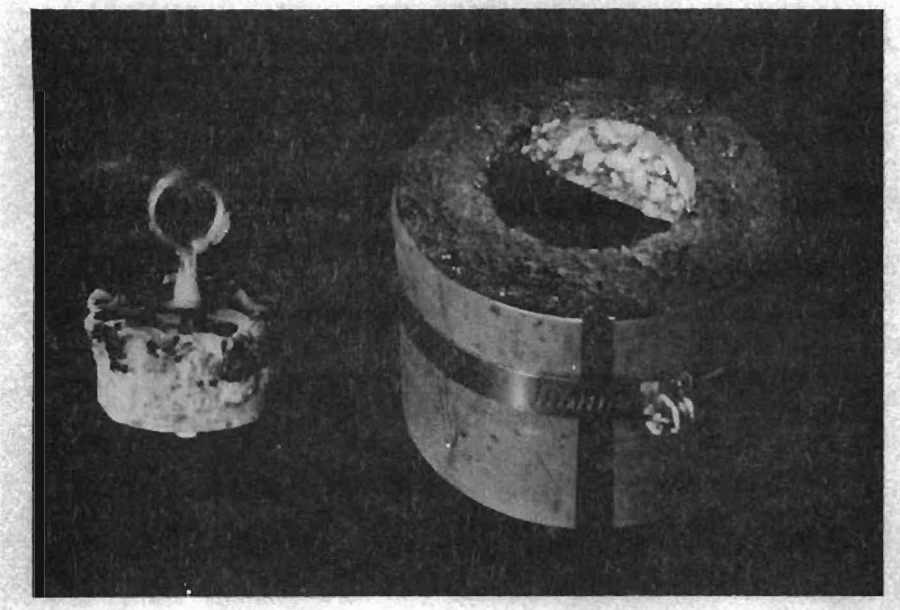


Fig. 3.7 Specimen after testing.

CHAPTER 4
PRELIMINARY RESEARCH

4.1 Background

The research for this portion of the study was started when a fly ash from an unidentified source was received. The first test done on this fly ash was the Gilmore needle set times at different fly-ash-to-water ratios, which at the same time provided a subjective measure of workability. Immediately following the Gilmore test, the peak exotherm and the compressive strengths were measured for the different ratios that were determined on a volumetric basis rather than by weight as was done in the formal testing. The Gilmore test results were compared to the peak exotherms; and the 20-minute, 30-minute, 45-minute, and one-hour compressive strengths yielded a stress versus time composite. All of these tests were performed at a material and ambient temperature of approximately 72^{o}F. The fly ash weighed 1.26 gm/cc. All the preliminary data are tabulated in Table 4.1.

4.2 Gilmore Needle Set Times and Peak Exotherm

The Gilmore set times and the peak exotherms for the different ratios of fly ash to water, which ranged from 3.5 to 4.10 (by volume), were determined as described in sections 3.4 and 3.6.

The fly ash for the Gilmore test was weighed and placed in a stainless steel bowl; the water, carefully measured with a graduated cylinder, was added to achieve the desired consistency and ratio. The materials were mixed by hand for one minute, or until thoroughly blended,

Table 4.1 Preliminary Research Data for Fly Ash.

PRELIMINARY RESEARCH DATA FOR FLY ASH

FA/Water by volume	SET TIME (min)		PEAK EXOTHERM		COMPRESSIVE STRENGTH (psi)				
	Initial	Final	°F	min.	20 min.	30 min.	45 min.	1 Hr.	1 Day
3.50	8	41	88	8	25	60	82	102	1000
3.60	6	26	86	11	30	52	72	110	810
3.70	6	21	87	10	32	41	92	120	1097
3.80	4	14	90	9	52	82	135	157	847
3.90	4	11	88	8	61	104	130	180	1010
4.00	5	14	91	9	80	112	156	156	1100
4.10	6	11	91	13	77	107	150	217	1100

and immediately thereafter the specimens were molded and tested.

The mix for the peak exotherm was made with 1600 grams of fly ash and water, which was measured with a graduated cylinder. The amount of water was dependent on the desired ratio. Part of the mix was utilized to perform the peak exotherm test, and the rest was used for the compressive strength test (section 4.3). As in the case of the Gilmore test the materials and air were at 72^{o}F, and the fly ash and water were mixed by hand for one minute, or until thoroughly blended.

As seen in Fig. 4.1, fly ash is extremely sensitive to the water content. For example, for a fly ash-to-water ratio of 3.50, which was obtained by mixing 1600 gm of fly ash with 363 cc of water, the final set time was 41 minutes; whereas for the ratio of 3.60, containing 1600 gm of fly ash and 353 cc of water, the final set time was 26 minutes. A 10 ml difference in the water content created a 15-minute change in the final set time. The difference in final set times was less dramatic in the subsequent ratios; nevertheless, the effect of the addition or loss of a small amount of water was quite significant.

The initial set curve, also depicted in Fig. 4.1, shows a similar sensitivity to water content. The initial set time changes from 10 minutes for the 3.50 ratio, to six minutes for the 3.60 ratio. The percent change in set times for a 10 ml difference in water was just as significant. As in the case of the final set curve, the changes were less noticeable for higher fly-ash-to-water ratios.

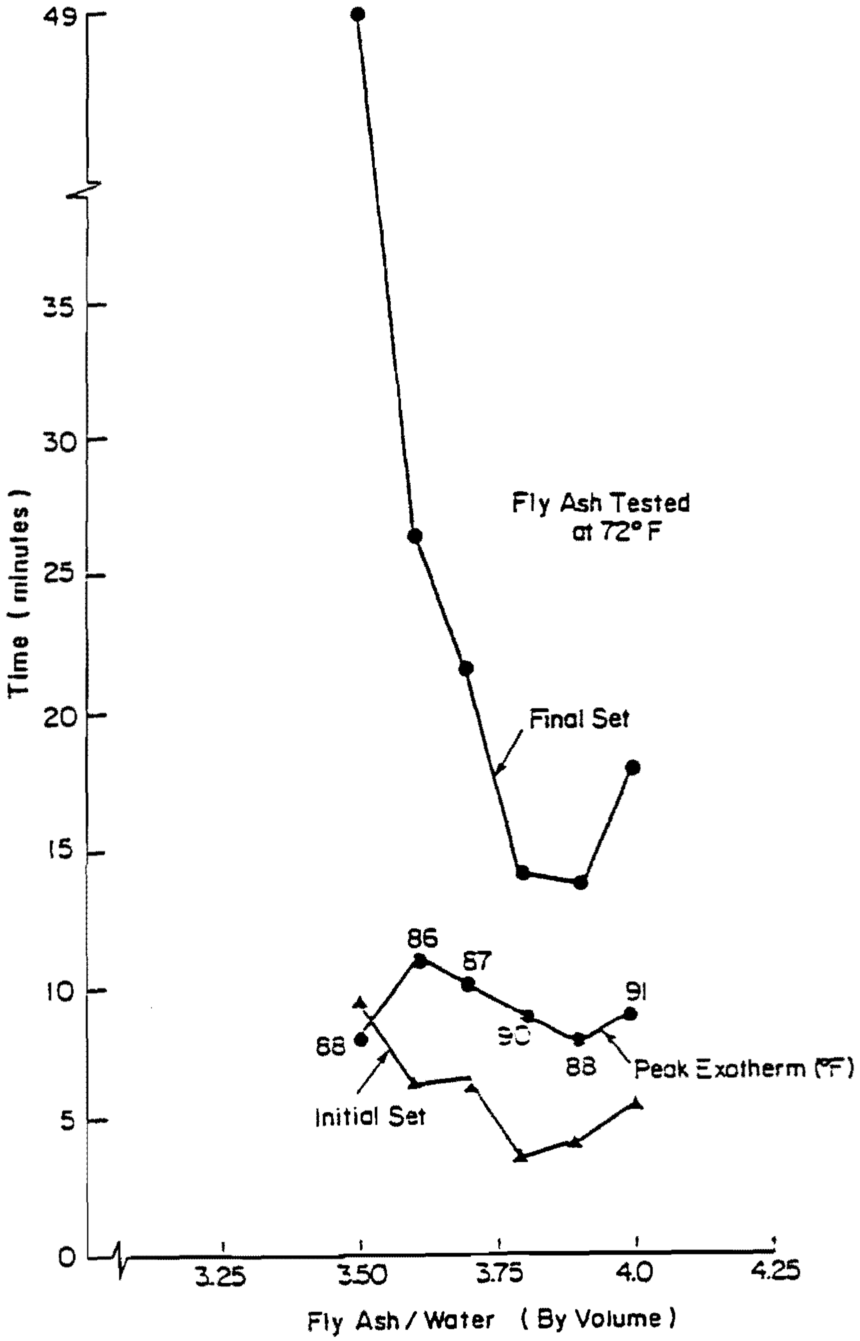


Fig. 4.1 Peak Exotherm and Gilmore Needle Set Times for Preliminary Research Fly Ash.

Both of the Gilmore set time curves portray the characteristics of an "optimal curve," in the sense that they have a point that is an apparent minimum, and thus the same set time was possible for two different ratios. The best ratio will then be chosen when considering additional parameters such as compressive strength.

The peak exotherm pattern seems to mirror the initial set times, but, for the same ratios, the peak exotherm occurred at different times than either the final or initial set times, and thus the two tests produce results that do not coincide. The discrepancies that arise after conducting both tests are further complicated when the results are matched with reality. If set times and peak exotherms indicate the amount of time that a mix can be workable, then neither of the tests gives a reliable measure. At all fly-ash-to-water ratios the mix ceased to be workable before the initial set time indicated by the Gilmore test.

4.3 Compressive Strength

The procedural details of this test can be found in section 3.2. The compressive strength was measured from 2-in. x 2-in. x 2-in. cube specimens at 72°F after 20 minutes, 30 minutes, 45 minutes, and one hour. Figure 4.2 summarizes the results, and it shows that: (1) the compressive strength increases with time and (2) for a given amount of fly ash, the less the volume of water, the greater the compressive strength.

From the one-hour data shown in Table 4.1, the compressive strength curve of Fig. 4.3 was constructed.

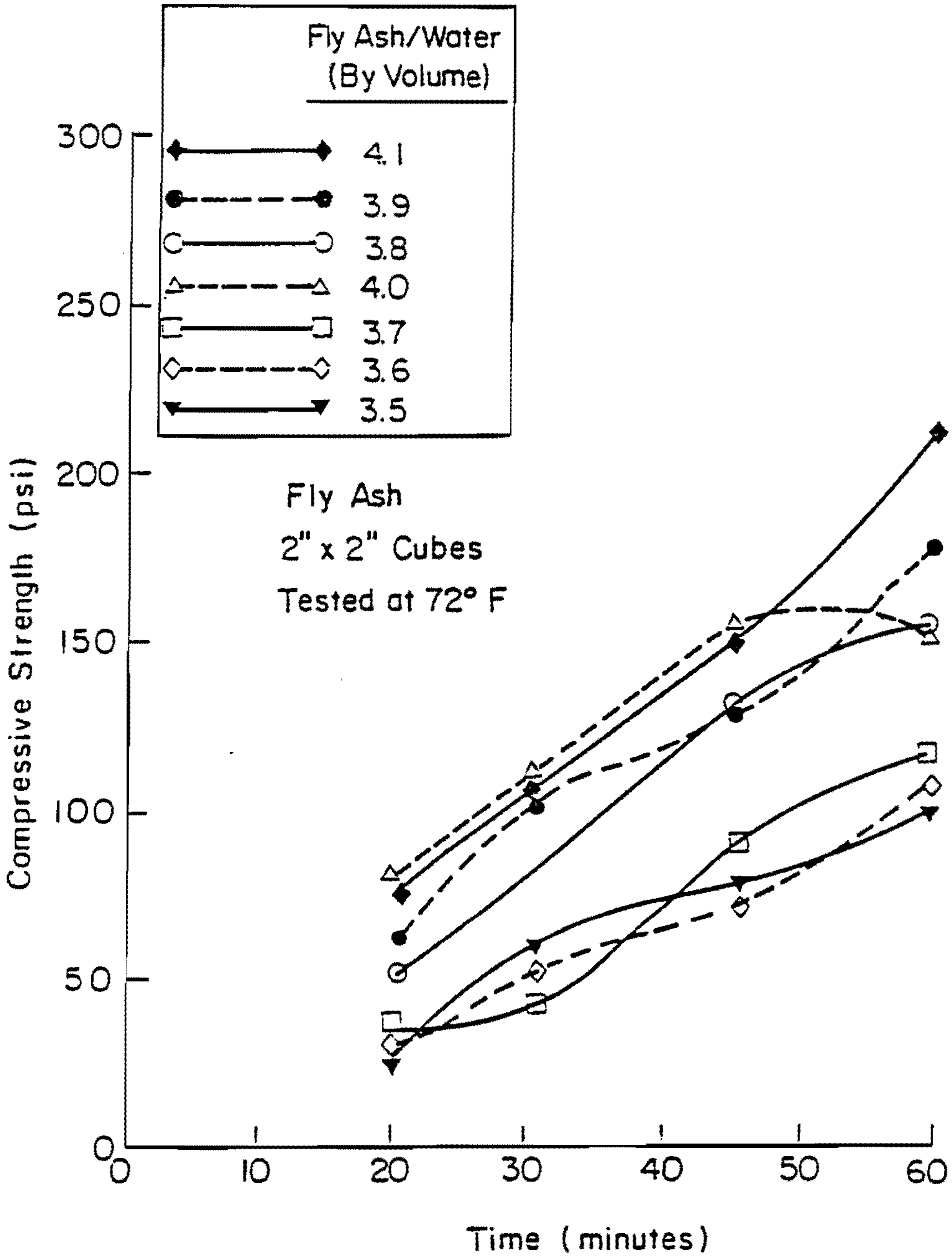


Fig. 4.2 Compressive Strength as a Function of Time for Preliminary Research Fly Ash.

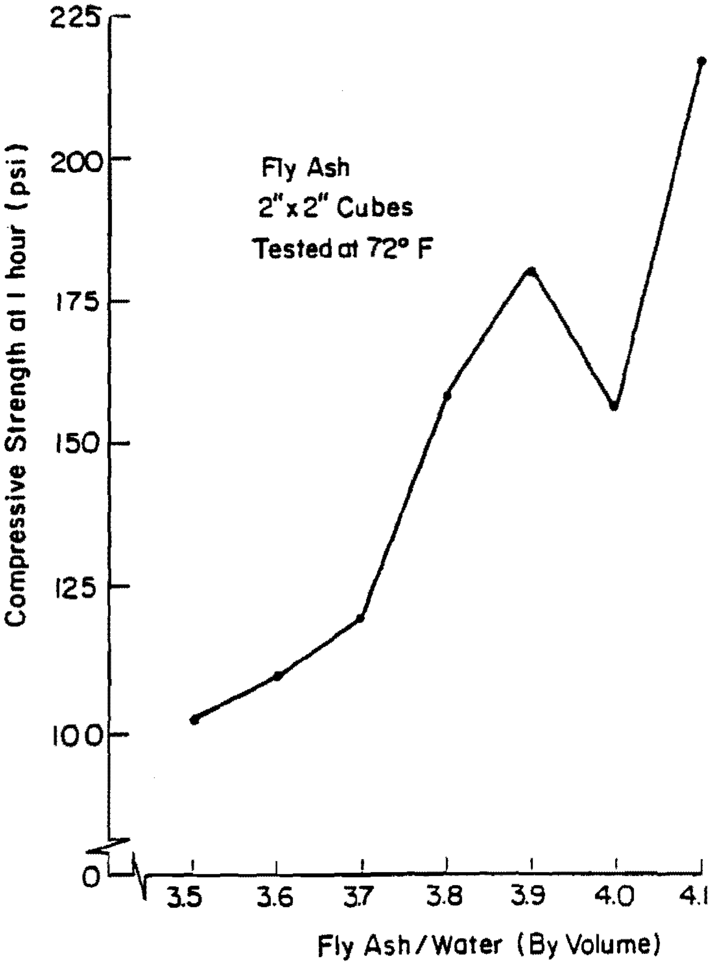


Fig. 4.3 Compressive Strength as a Function of the Fly Ash to Water Ratio for Preliminary Research Fly Ash.

This graph illustrates the strength changes that occur with a slight variation in the water content.

From the research presented thus far it can be concluded that the fly-ash-to-water ratio is probably the most critical factor to consider when designing a mix of fly ash and water. The water content has a very dramatic effect on set times, strength, workability and placeability.

4.4 Ratio of Ingredients

For tests which involved different fly ash/sand/coarse aggregate ratios, water was added such that the workability of each mix was approximately the same. Keeping workability consistent for all the different mixes became important because if too much water was added the strength was found to be greatly reduced whereas if too little was added the mix was unworkable. Because fly ash is a rapidly setting material conventional methods of determining slump cannot be used unless the time at which the slump was taken is identified. For this reason the workability, of each batch was categorized subjectively by observation. A letter scale was used to record the workability in which "A" indicates a very watery consistency, "B" indicates optimal workability and "C" indicates a material too stiff to be considered mortar. Determining the workability by more objective means could be useful in future studies; however, this method proved to be satisfactory for this initial study.

Table 4.2 shows the ratio of ingredients used to produce mixes having the optimum workability. For the purpose of making road repairs, designating materials by volume rather than by weight proved to be much more

Table 4.2 Ratio of Ingredients Data.

FA : S : CA, by Volume	W : TV, by Volume	W : FA, by Volume	S : TV, by Volume	Workability @ 30 Seconds
1 : 1 : 0	.18	.31	.55	B−
1 : 1 : 1	.15	.38	.40	B+
1 : 1 : 2	.13	.39	.33	B+
1 : 1 : 3	.11	.40	.28	B
2 : 1 : 0	.20	.27	.37	B
2 : 1 : 1	.17	.30	.28	B
2 : 1 : 2	.16	.33	.24	B+
2 : 1 : 3	.15	.36	.21	B
1 : 2 : 0	.17	.43	.80	B−
1 : 2 : 1	.16	.48	.67	B
1 : 2 : 2	.15	.56	.53	B+
1 : 2 : 3	.13	.56	.47	B
1 : 0 : 0	.20	.20	.00	B−

Key

FA – Fly Ash
CA – Course Aggregate
S – Sand
W – Water
TV – Total Volume

Workability Index

A – Watery
B – Optimum
C – Stiff

practical. Throughout all the lab and field testing, except where indicated otherwise, this table was used to determine how much distilled water to add to each mix. Once the total volume of the road repair is estimated, the ratios in this table are enough to determine how much of each ingredient should be added. Section 6.2 gives a more detailed description of this table and includes several examples. When using this table it is important to keep in mind that dry ingredients were loosely packed and that mixing was done primarily with hand tools. If an electric mixer is used more water should be added to prevent premature hardening in the mixer.

CHAPTER 5

RESEARCH RESULTS - LAB

5.1 Introduction

This chapter contains the results of the formal lab research, i.e., that part of the investigations in which the material origins are known. The testing procedures followed the guidelines of Chapter 3.

All of the initial materials tested came from three plants in Texas located near the cities of San Antonio, Amarillo, and Cason. After different kinds of fly ash were examined, the research centered around finding the optimum ratios of fly ash, sand, coarse aggregate and water. Finally, different additives to fly ash were investigated to see if it could be further improved as a road repair material.

5.2 Deely Fly Ash

5.2.1 Calcium Oxide Content

This test was performed by carefully following the seven-step procedure indicated in section 3.7. The temperature differential in the chemical reaction was 38.5°C, which corresponds to a total calcium oxide content of 18.4 percent.

5.2.2 Optimal Curve

The optimal curve of the average compressive strengths at one hr. and 72°F for different water-to-fly-ash ratios is shown in Fig. 5.1 and the corresponding data are tabulated in Table 5.1. From the graph, it can be seen that the highest strength, 640 psi, was attained at a

Table 5.1 Deely Fly Ash: Optimum Water/Fly Ash Ratio by Weight at 72°F.

DEELEY FLY ASH: OPTIMUM Water/Fly ash RATIO by weight AT 72°F COMPRESSION FAILURE AT 1 HOUR ON 2"X 2" CUBES									
RATIO	.143	.154	.167	.174	.182	.190	.200	.210	.222
STRENGTH (psi)			631 660 635	553 535 508	379 420 396 468 556	491 405 375	496 499 539	379 441 383	388 400 310
AVERAGE	0	0	642	532	444	424	511	401	366
COMMENTS	Very dry	Very dry	Very stiff	Sticky sets fast	Sticky sets fast	Sticky but workable	Sticky but workable	Very sticky hard to work	Very sticky hard to work

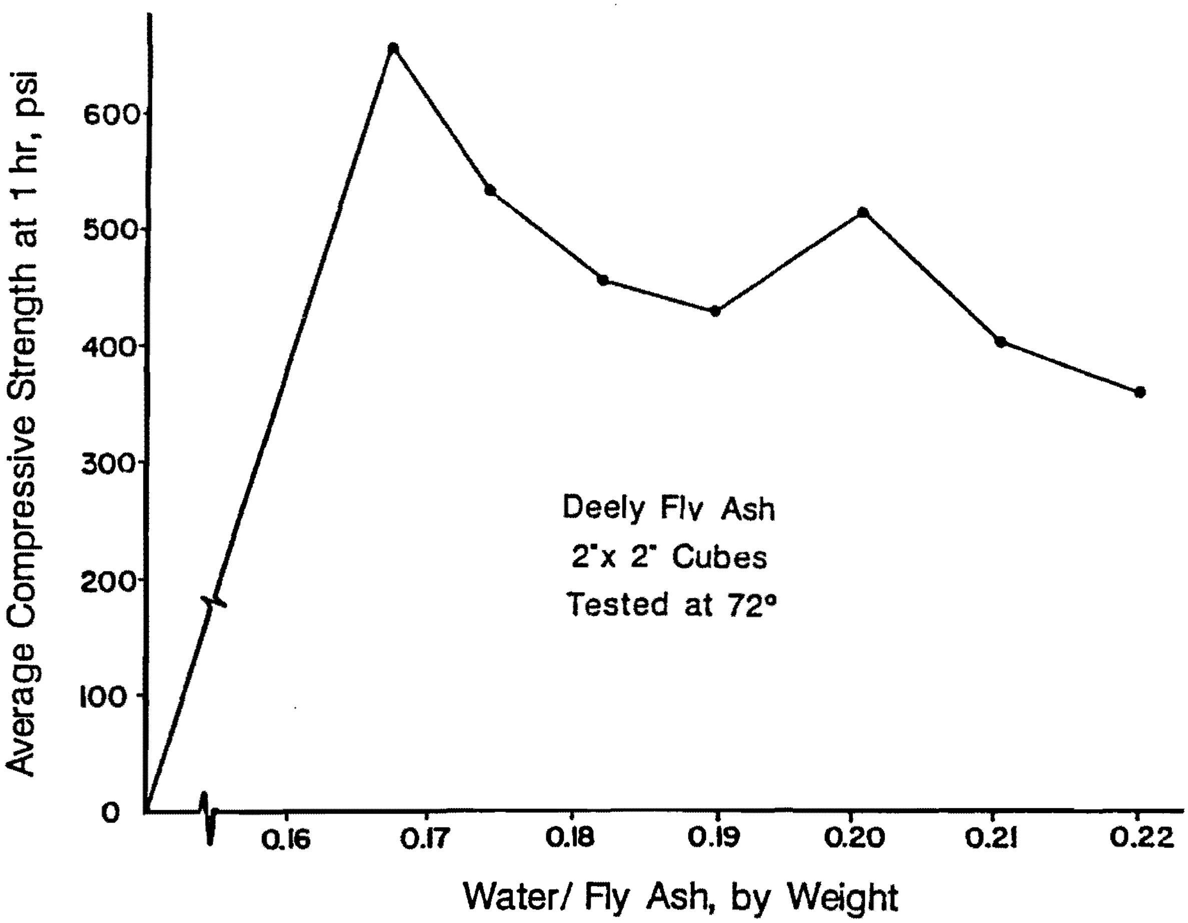


Fig. 5.1 Optimal Curve for Deely Fly Ash.

water-to-fly ash ratio of approximately 0.17, and this strength decreased as the water content increased. The material and workability ranged from fragmented and unworkable, to extremely plastic and sticky.

The water content is also responsible for the resulting workability, and in general it can be said that diminishing the amount of water will result in a still and fragmented mix, and augmenting the amount of water will produce a plastic and sticky material.

This curve and its data suggest that there is a trade-off between strength and workability, and thus this type of analysis is needed to determine the optimum conditions for the particular use. For the purposes of this research, it was decided that a water-to-fly ash ratio of 0.20 by weight was adequate.

5.2.3 Compressive Strength

Fig. 5.2 shows the results of compressive Fig. 5.1 strength tests for the Deely fly ash at 40°F, 72°F, and 100°F.

5.2.4 Flexural Strength

Fig. 5.3 shows the results of flexural tests performed on the Deely fly ash at 40°F, 72°F, and 100°F. The plot shows the high one-hour strength of 130 psi at 72°F, the low one-hr strength of 53 psi at 100°F, and the non-existent one-hr. strength at 40°F; these strengths contrast the high 207-psi one-week strength at 40°F, the moderate 194-psi strength at 72°F, and the low 175-psi strength at 100°F. It can be concluded that the catalyst effect of temperature on the hydration of the fly ash precludes the formation of a strong chemical bond.

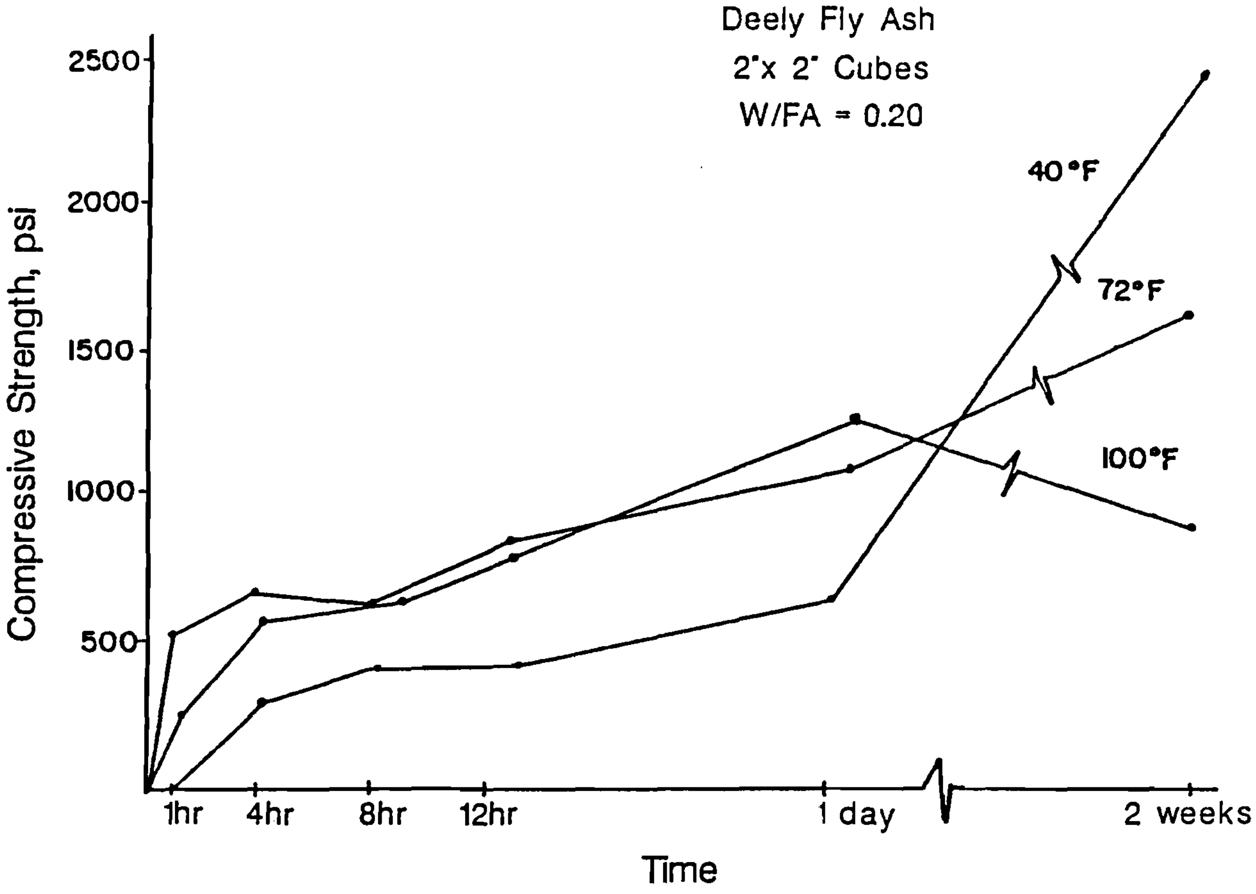


Fig. 5.2 Comparison of the Compressive Strength of Deely Fly Ash at Different Temperatures.

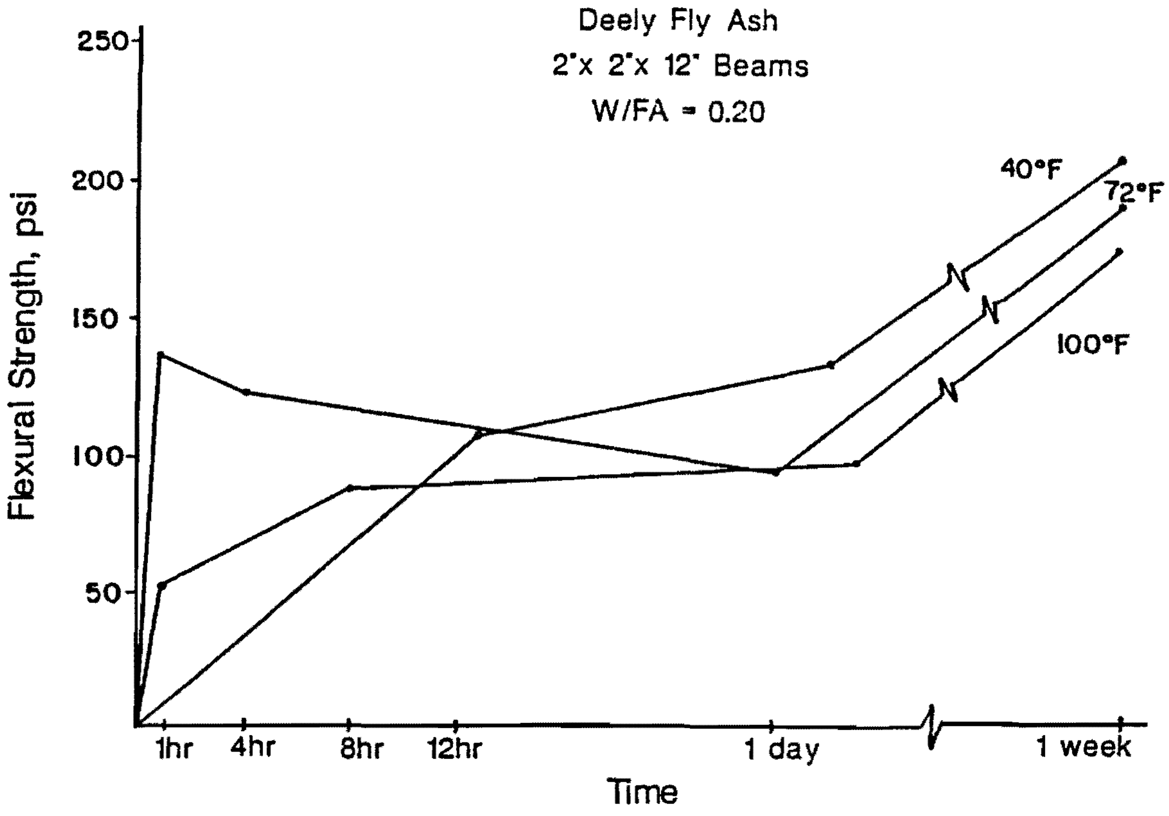


Fig. 5.3 Comparison of the Flexural Strength of Deeley Fly Ash at Different Temperatures.

5.2.5 Gilmore Needle Set Times and Peak Exotherm

The Gilmore test and peak exotherm test results did not coincide with each other at any of the temperatures tested, and the pattern was consistent with what was reported in section 4.2.

The initial set times were eight minutes, eight minutes, and 70 minutes; and the final set times were 15 minutes, 16 minutes, and 150 minutes for the 72°F, 100°F, and 40°F tests respectively.

The peak exotherm at 40°F remained at 41°F throughout, and the 100°F and 72°F specimens had their peaks at 14 minutes and 17 minutes.

There was no apparent correlation between the tests. At 72°F, the mix could not be worked after five minutes elapsed, at 100°F this was reduced to three to four minutes, and at 40°F the mix set after 15 or 20 minutes.

5.3 Harrington Fly Ash

5.3.1 Calcium Oxide Content

The calcium oxide content for the Harrington fly ash was determined to be 20.8 percent, obtained by following the seven-step procedure of section 3.7, for which there was a temperature differential of 44.5°C.

5.3.2 Optimal Curve

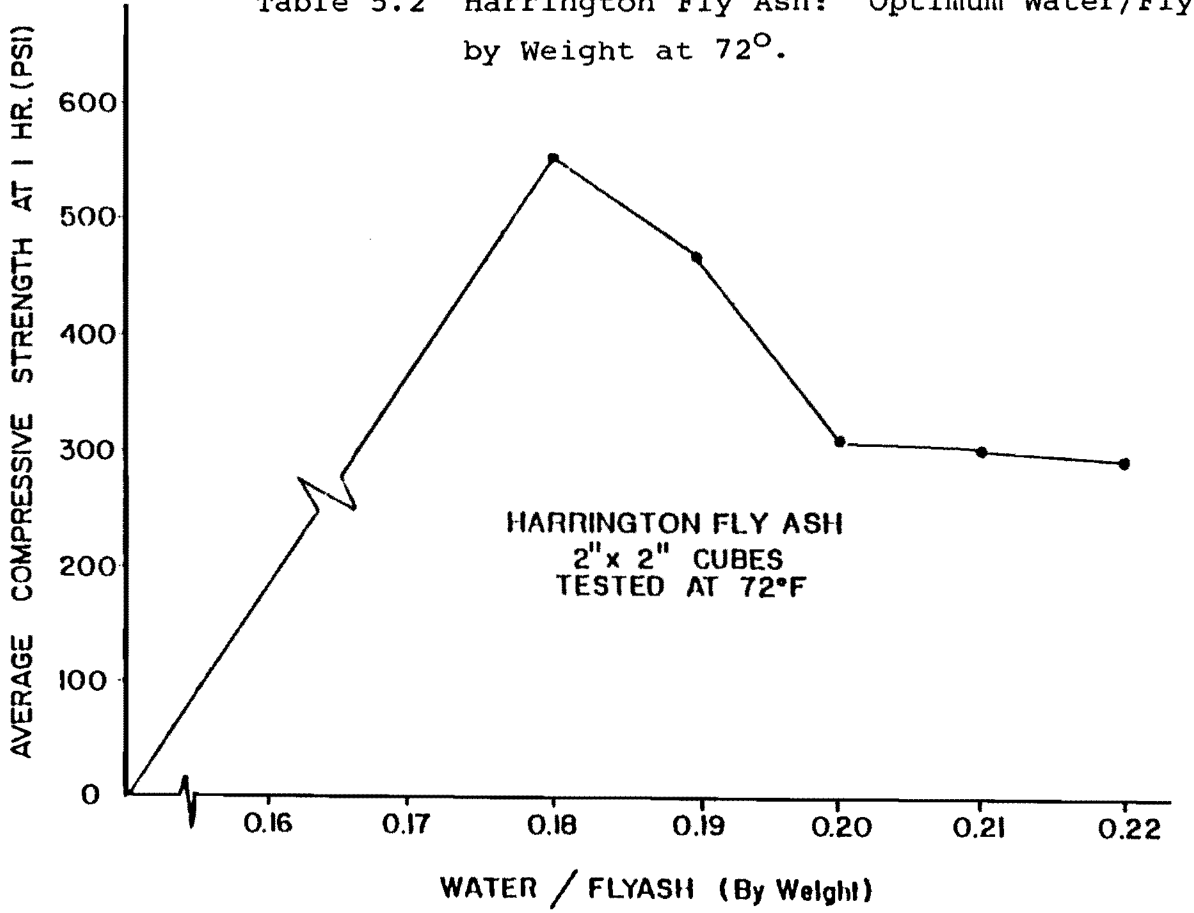
The optimal curve determines the ideal water-to-fly-ash ratio at which the mix was tested, as shown in Fig. 5.4. From the graph and the comments in Table 5.2, it can be seen that the maximum one-hr average compressive

HARRINGTON FLY ASH : OPTIMUM Water/Fly Ash RATIO by weight
AT 72°F COMPRESSION FAILURE AT 1 HOUR ON 2" X 2" CUBES

RATIO	0.17	0.18	0.19	0.20	0.21	0.22
STRENGTH (psi)		625 490 431	431 522 462	360 400 321 319 205 270	312 311 300	312 275 309
AVERAGE	0	557	472	1600	308	299
COMMENTS	Dry not cohessive	Stiff and dry	Workable	Workable	Sticky and wet	Very sticky

Fig 5.4 Optimal Curve for Harrington Fly Ash.

Table 5.2 Harrington Fly Ash: Optimum Water/Fly Ash Ratio by Weight at 72^{o}.



strength of 560 psi had a water-to-fly-ash ratio of 0.18, which was too stiff to work; hence the 0.20 ratio was selected.

The curve shows that the average compressive strength decreases with an increase in the water content. The amount of water used also influences the workability of the mix; very little water creates a stiff, uncohesive material, and, on the other extreme, excess water will bring about a very plastic and sticky mix. Since the fly ash of this strength exhibits a significant sensitivity to water, particularly in the water-to-fly-ash range of 0.18 to 0.20, the determination of the ideal ratio is recommended.

5.3.3 Compressive Strength

Fig. 5.5 shows results of the compressive tests for the Harrington fly ash at 40^{o}F, 72^{o}F, and 100^{o}F.

The 72^{o}F compressive strength curve indicates the typical strength increase with time behavior, which is almost linear for the first 8 hrs. At 12 hrs, the strength increases very significantly, to over 3000 psi. The value appears to be uncharacteristically high, and it may have been the result of nonuniform material.

The 40^{o}F compressive strength curve shows a strength gain with time that is gradual and uniform. The cool temperature allows the chemical bond to occur at a rate at which it can sustain an average stress of up to 3680 psi at one week. This series of tests had a low scatter in the data and a curve can be fitted with little difficulty.

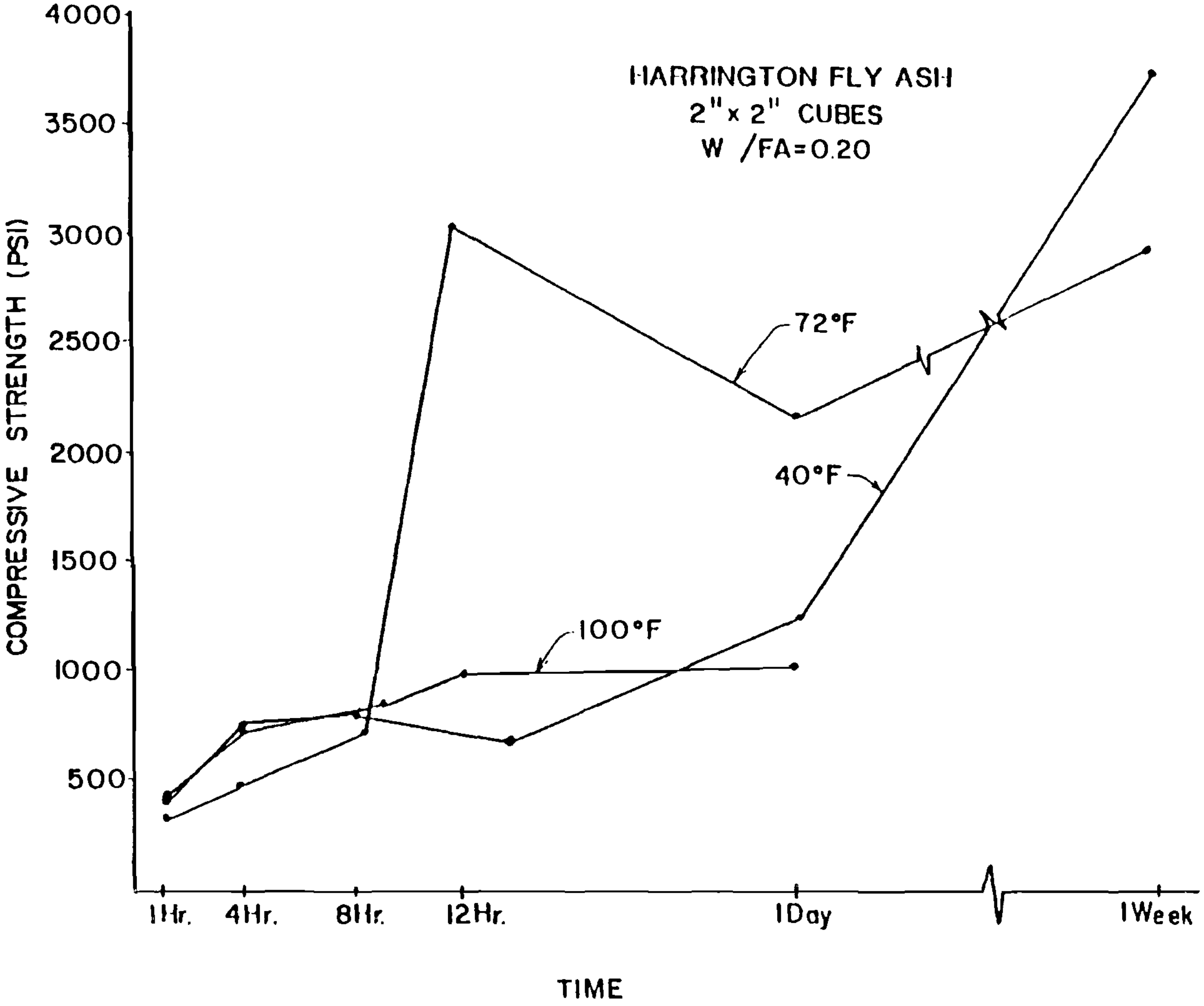


Fig 5.5 Comparison of the Compressive Strength of Harrington Fly Ash at Different Temperatures.

The 100°F plot depicts higher average compressive strengths than the ones shown for 72°F. The reason for the higher early strengths at 100°F is that temperature makes it set faster. On the other side of the temperature spectrum, the 40°F specimens exhibited comparable strengths up until 8 hr., at which time the effect of the heat seemed to act on the 100°F specimens. In summary, it seems that the speed at which the chemical reaction takes place is very critical to the long-term strength of the specimens: the slower the speed the stronger the specimens.

5.3.4 Flexural Strength

The results obtained from the flexural strength testing of the Harrington fly ash at 40°F, 72°F, and 100°F are shown in Fig. 5.6. From this graph, it could be theorized that the factors that may be responsible for the flexural strength are mainly mechanical, chemical, and capillary [7]. The mechanical forces consist of the interlock that exists from the angularity of the particles, which in this case is probably not significant. The chemical forces are due to the molecular bond that occurs through the hydration of the calcium oxide and the formation of any other stable compounds in the mix of fly ash and water. The capillary forces are the ones attributed to the tension forces within the specimens that are not yet thoroughly dry.

From Fig. 5.6, the 40°F curve shows an impressive gain of 420 psi during the first 14 hrs. After the first 14 hrs, however, there is a drop in the flexural strength that could be attributed to the slow rate at which the chemical bond forms, and this bond cannot make up for the

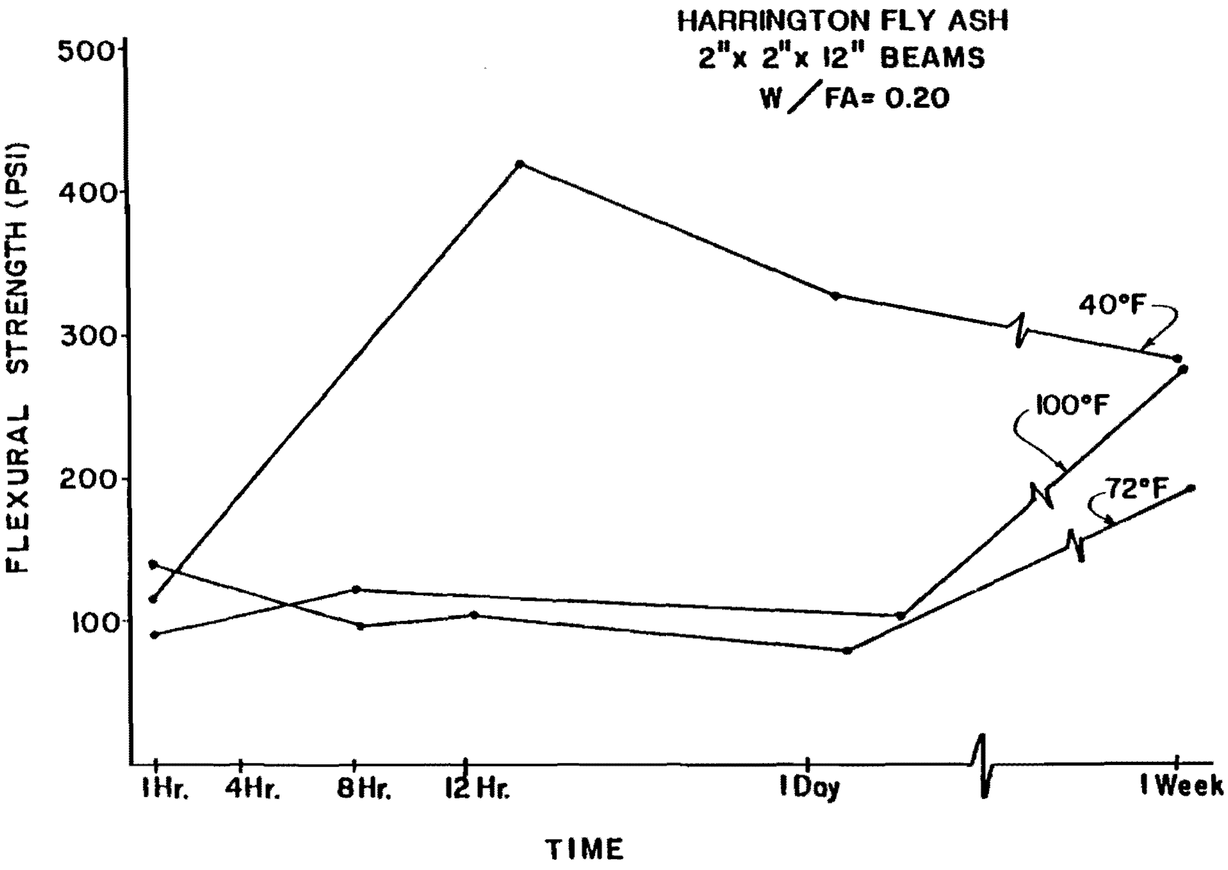


Fig 5.5 Comparison of the Compressive Strength of Harrington Fly Ash at Different Temperatures.

loss in the capillary forces due to the drying process. Correspondingly at 72°F and 100°F, the warmer temperatures allowed for a faster completion of the chemical reaction.

5.3.5 Gilmore Needle Set Times and Peak Exotherm

The Gilmore needle initial set time for 72°F was the same as for the peak exotherm, which occurred at about 5 to 6 minutes. The final set time was 23 minutes. There was a good correlation between both tests at 40°F, but, in this case, the final set time of 45 to 46 minutes coincided with the time of the peak exotherm, which occurred at 44 minutes. The initial Gilmore set time at 40°F was at 45 minutes. At 100°F there were no reproducible results, and the initial set was at 8 minutes, the final set at 17 minutes, and the peak exotherm at 13 minutes. Just as in the case of the Deely fly ash, the test results and what happened in reality were different. The mix was workable for up to four minutes at 72°F, 3.5 minutes at 100°F, and 20 to 25 minutes at 40°F.

5.4 Welch Fly Ash

5.4.1 Calcium Oxide Content

The total content of calcium oxide for the Welch fly ash was determined to be 21.2 percent. This was calculated from the formula given in the seven-step procedure of section 3.7, in which the temperature increment was 45.5°C.

5.4.2 Optimal Curve

The optimal curve of Fig. 5.7 shows graphically the data from Table 5.3. As explained in section 3.5, this curve is an aid for choosing an ideal water-to-fly-ash ratio for compressive strength, which in this case was 0.19. The plot illustrates the sensitivity of the average one-hr compressive strength of this material to a small change in the water content. In this case, the ratio of 0.19 also was a practical value from the standpoint of workability, but this is not always the case. It is necessary to make a subjective judgment of the workability of the material and select the best ratio based on strength and workability.

5.4.3 Compressive Strength

The compression tests for the Welch fly ash were conducted according to the procedures described in section 3.2. The data obtained from the tests are presented in Fig. 5.8. The curves drawn in the figure summarize the strengths of the Welch fly ash at the three temperatures tested, show that the material had a strength gain at all temperatures, and show that temperature played a very important role in the strength development of the specimens.

5.4.4 Flexural Strength

The flexural test results are presented graphically in Fig. 5.9.

The specimens tested at 72^{o}F experienced a 360 psi gain within one hr. The material showed a slight decrease to 330 psi at 4 hrs, and increases thereafter until 12 hrs, when it reached 470 psi and started a

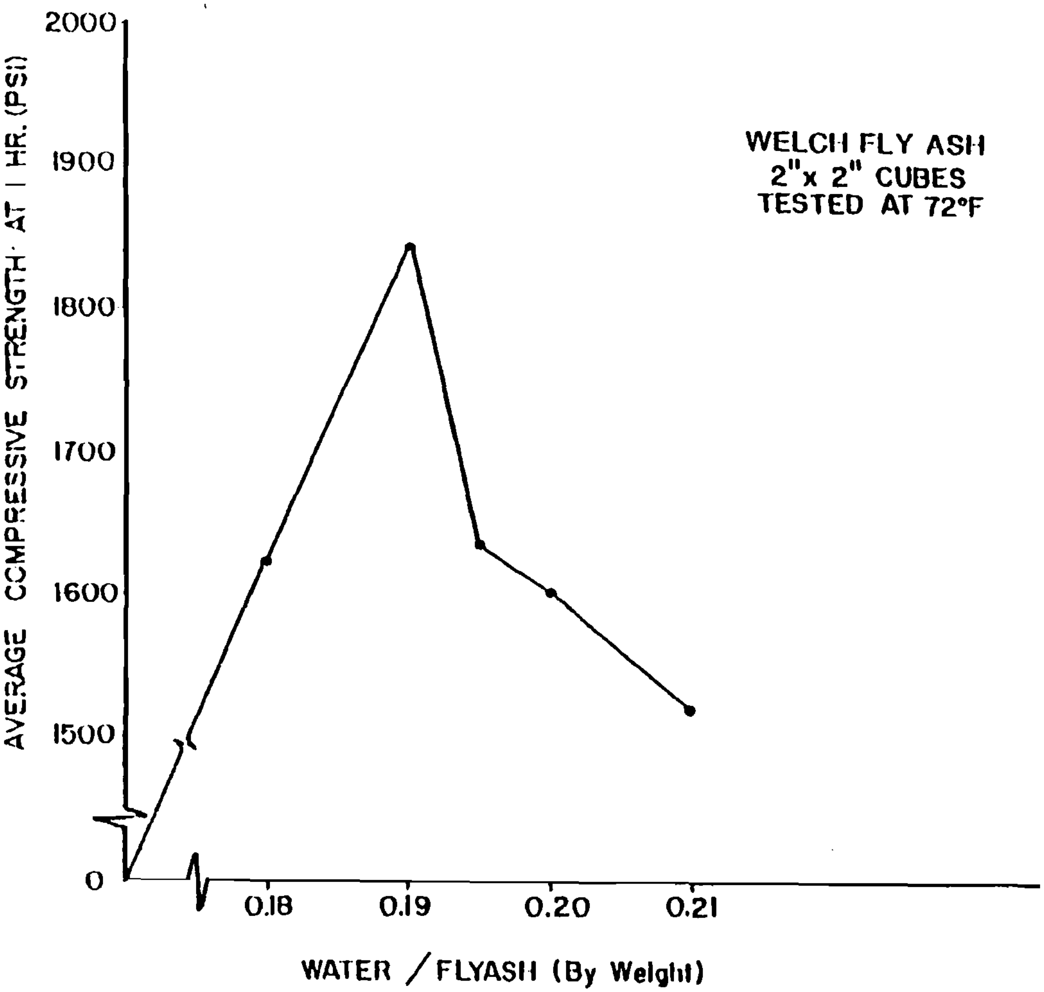


Fig. 5.7 Optimal Curve for Welch Fly Ash.

Table 5.3 Welch Fly Ash: Optimum Water/Fly Ash Ratio by Weight at 72°.

WELCH FLY ASH : OPTIMUM Water/Fly ash RATIO by weight AT 72°F COMPRESSION FAILURE AT 1 HOUR ON 2"X 2" CUBES					
RATIO	0.18	0.19	.195	0.20	0.21
STRENGTH (psi)	1575 1675 1620	1810 2060 1665	1885 1500 1525	1525 1590 1685	1450 1640 1475
AVERAGE	1623	1845	1637	1600	1522
COMMENTS	Workable sets fast	Workable dry	Workable	Workable excess water	Sticky and wet

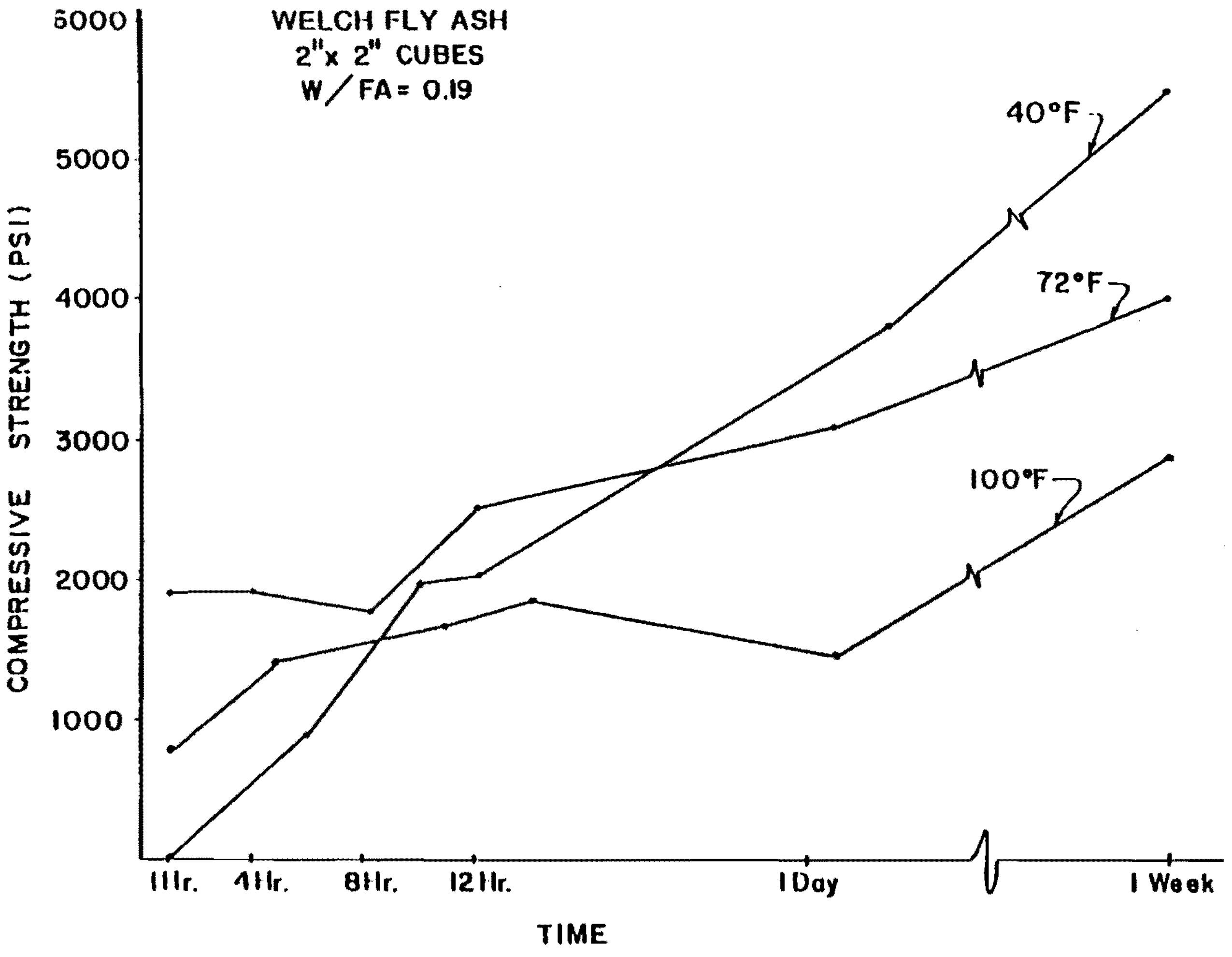


Fig. 5.8 Comparison of the Compressive Strength of Welch Fly Ash at Different Temperatures.

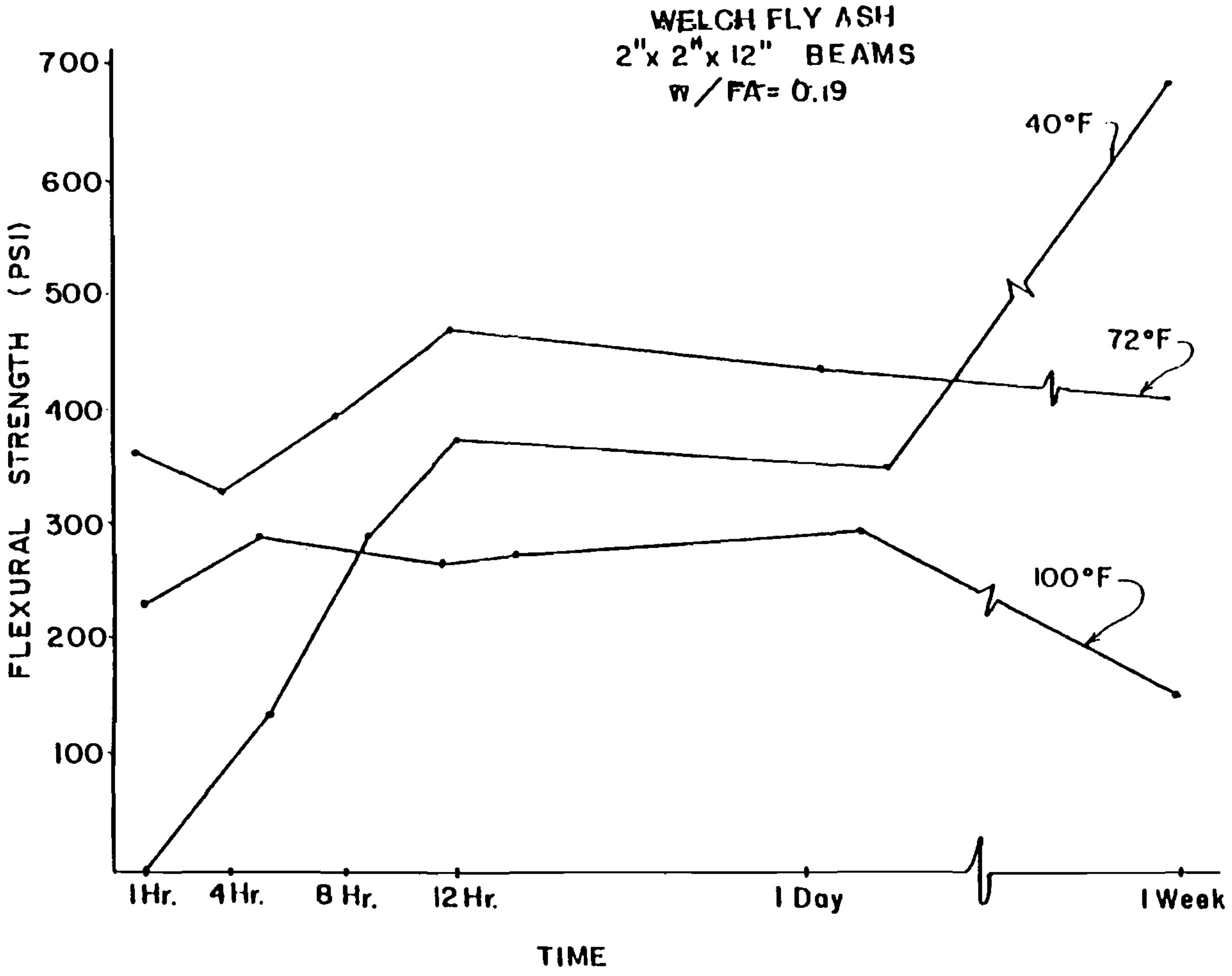


Fig. 5.9 Comparison of the Flexural Strength of Welch Fly Ash at Different Temperatures.

decrease that gave a 390 psi strength at one week. The 72°F data are shown in Fig. 5.24 and Table 5.19.

The plot of the 40°F data exhibits a steady linear strength gain that ranges from zero at one hr. to 380 psi at 12 hrs. The flexural strength dropped slightly during the second 12-hr period to 356 psi at one day, and continued to rise after that to reach 680 psi at one week.

At 100°F, the Welch fly ash had a one-hr flexural strength of 230 psi, which rose to 290 psi at 5 hrs, dropped to 270 at 12 hrs, rose to 300 psi at 26 hrs, and dropped to 151 psi at one week. While the data are in the three cases not conclusive, it appears that as the curing temperature increased, the flexural strength decreased with increased curing time.

5.5 Investigation of Fly Ash and Sand

5.5.1 Compression Strength

Figure 5.10 shows the compressive stresses of different kinds of fly ash mixed in various proportions with sand. Welch No. 2 and Welch No. 3 refer to different shipments of fly ash from the Welch power plant. As can be seen from this figure there seems to be reasonable consistency in the quality of fly ash coming from this plant. This is important because the research indicates that fly ash obtained from the Welch plant has the best possibility of being an adequate road repair material. Perhaps more importantly, Fig. 5.10 indicates that a fly-ash-to-sand ratio of 1:1 or 2:1 works significantly better than a ratio of 1:0 or 1:2 no matter what kind of fly ash is used. This possibility will be examined more

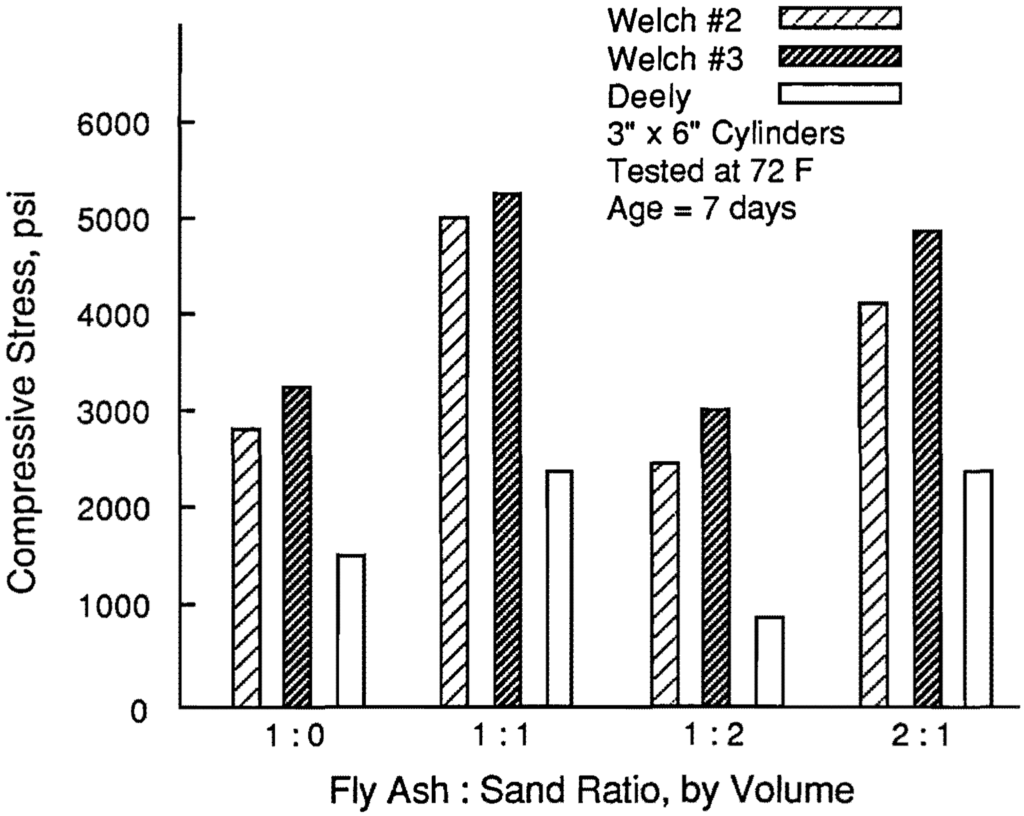


Fig. 5.10 Ultimate Compressive Stresses for various Fly Ash: Sand Ratios

extensively in the tests which follow. Please note that water having a pH of 6.0 was added in accordance with the ratios given in Table 4.1 for all tests in Fig. 5.10.

5.5.2 Optimal Water-to-Fly Ash Ratio

From the research conducted so far it appears that fly ash tends to be very sensitive to water content. Figure 5.11 shows this relationship for Deely fly ash mixed with different amounts of sand. In general it can be seen that those mixes with less water tend to be stronger no matter how much sand is used. The only exception is the initial value on the 1:1 curve, which resulted when so little water was added that the material could not be properly placed within the molds. Another feature shown by this graph is that, even though the 2:1 and 1:1 ratios yield much higher strengths, they also tend to be much more sensitive to any excess water which is added. Since it can be anticipated that exact measurements will not be made by maintenance workers who would use fly ash in the field, it is quite likely that some excess water will be added on a regular basis. In comparing Fig. 5.11 to Table 4.1 it should be noted that those points located on the far right of each of the three curves represent extremely wet mixes and normally would not be encountered.

5.5.3 Underwater Curing

Because this report is specifically aimed at repairing wet asphalt with fly ash the question arises as to whether or not fly ash will cure properly if it is submerged under water. This kind of situation could occur if a road repair was made in a section of highway with

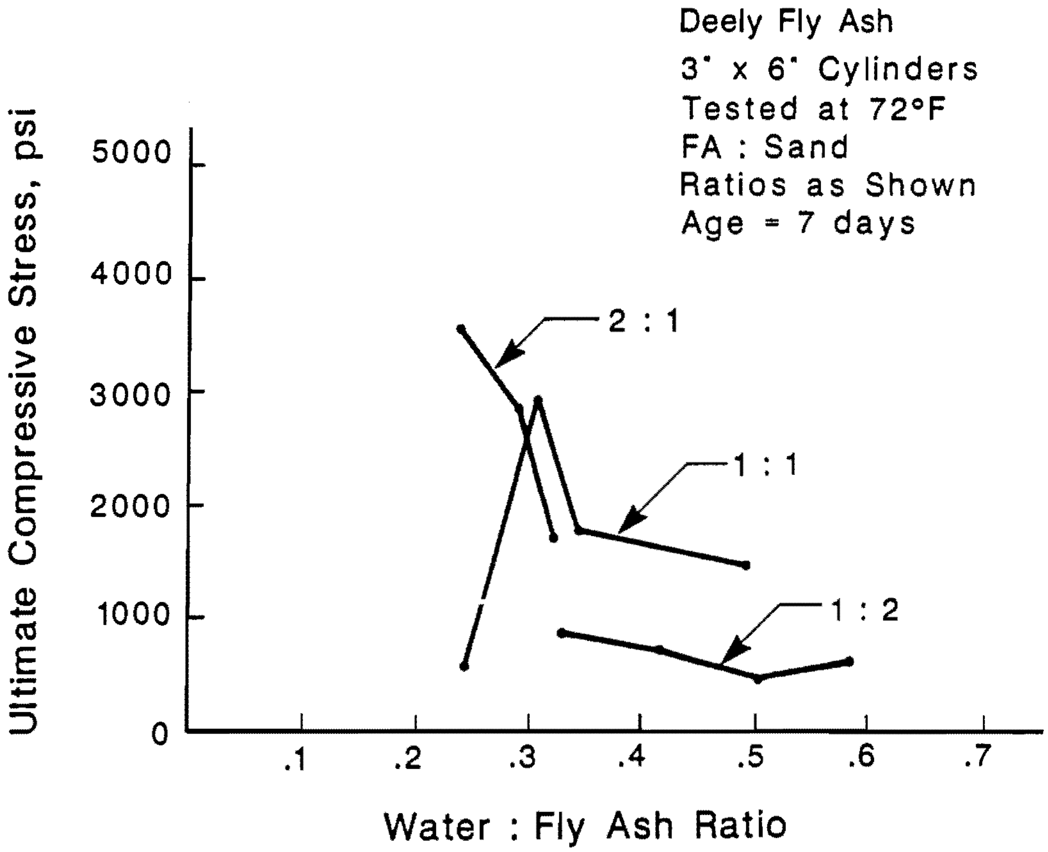


Fig. 5.11 Optimal Water Content for various FA: Sand Ratios

poor drainage just before a thunderstorm. Although no graphs are available, various tests indicate that fly ash cures as well under water as it does out of the water.

5.5.4 Compressive Modulus of Elasticity

Figure 5.12 shows the stress/strain diagram for different mixes of Harrington fly ash. Using the straight portions of the curves up to one-half fc ultimate strength (.5 f'c), the value for Young's Modulus is approximately 4080 ksi for both cases. Figure 5.13 shows the results of a similar test in which fly ash from the Welch plant was examined. Considering the data up to .5 f'c (Fig. 5.10) the value of Young's Modulus for the 2:1 ratio is 3780 ksi and for the 1:2 ratio is 3080 ksi. By far the most important observation from these tests is that hardened fly ash is a very stiff material. Ideally a repair material should have about the same elastic modulus as the asphalt into which it is cast. Because asphalt (particularly when it is hot) has such a low modulus compared to fly ash it is not likely that the modulus can be brought closer together. Even if a method could be determined to reduce the modulus of fly ash by one-half it would still be many times greater than that of asphalt. The phenomenon of a rigid elastic material in the midst of a soft plastic material may provide another explanation for failure of the road repair. With the continued application of traffic it is not unreasonable to expect the asphalt near the fly ash to deform, leaving the rigid fly ash protruding slightly above the road surface. Exposed in this manner the rate of fly ash disintegration can only be increased. Although this effect will be examined further during the field tests it is possible

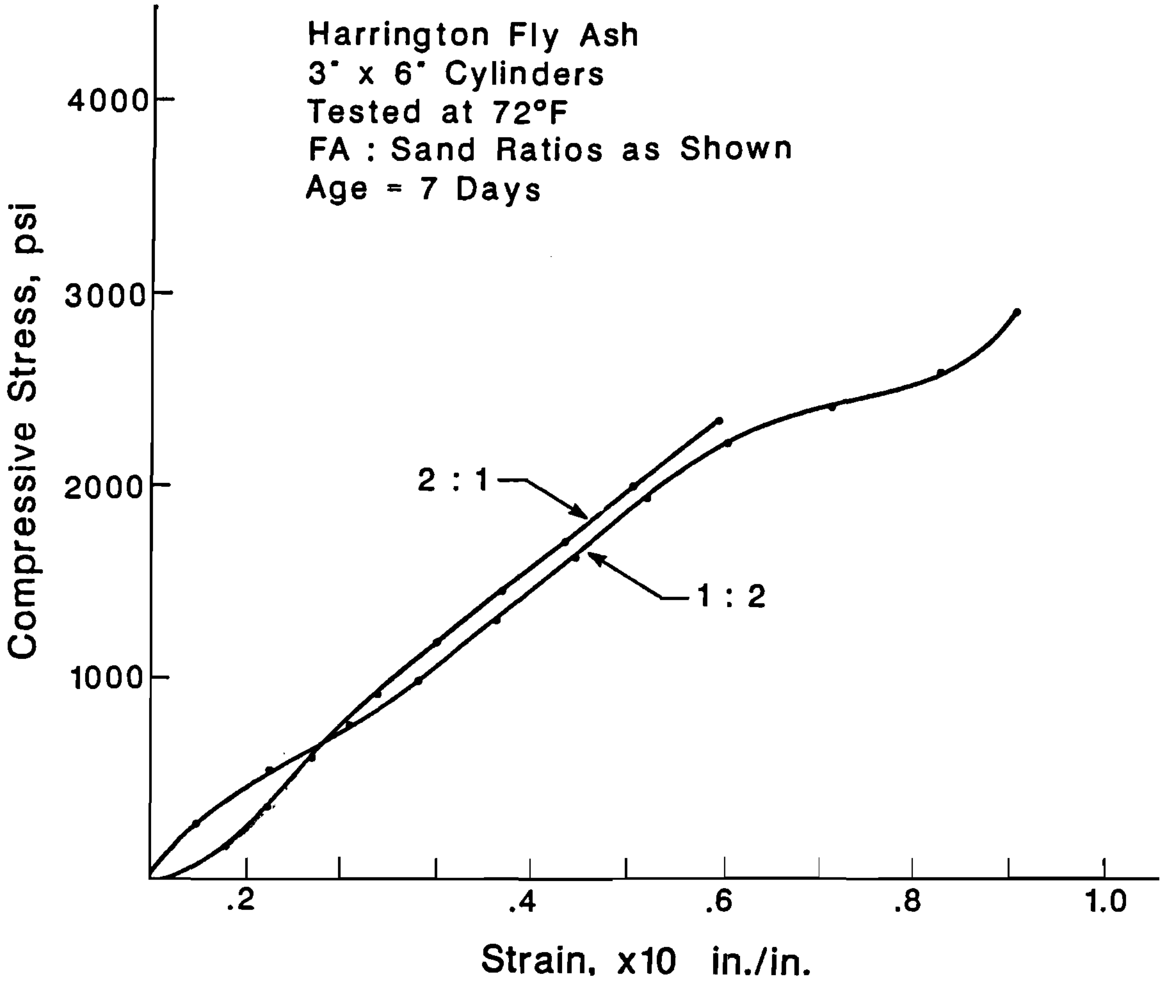


Fig. 5.12 Elasticity in Compression Test for Harrington Fly Ash at 7 days.

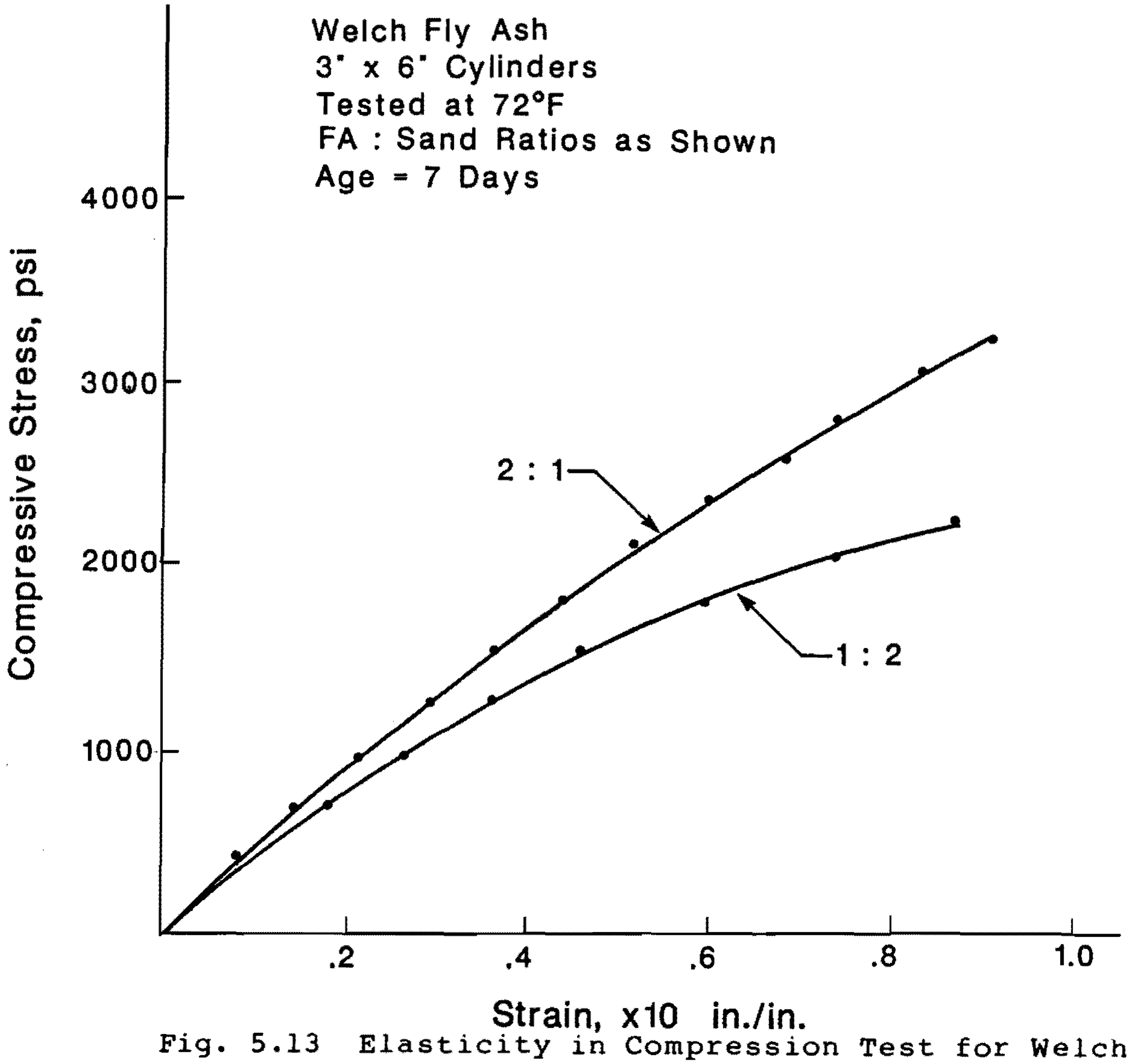


Fig. 5.13 Elasticity in Compression Test for Welch Fly Ash at 7 Days.

that simply casting the fly ash slightly below the road surface will eliminate this problem.

5.5.5 Shear Strength at the Interface

Shear tests in accordance with the method discussed in chapter 3 were conducted on the different types of mortar examined thus far. As can be seen by the large variations between the high and low values shown in Fig. 5.14, the test appears to be somewhat crude. Only by making hundreds of runs and refining the procedure would it be possible to make absolute conclusions. Nevertheless, the bar graph does show the tremendous bond between fly ash and asphalt. Part of the reason for this bond may be the fact that fly ash was captured out of the air and hence is extremely fine. When mixed with water these particles are capable of penetrating microscopic cavities in the walls of the asphalt. The shear bond at the interface appears to be substantially larger for the 1:1 and 2:1 ratios. This evidence supports the use of these fly-ash-to-sand ratios for small road repairs in which the fly-ash-to-asphalt bond may be very important. The fact that fly ash is a strong rigid material coupled with the fact that mechanical interlocking almost certainly takes place help make the bond at the interface stronger than the bond between the asphalt and itself. Indeed, for each of the mortars used, failure sometimes took place in the asphalt rather than at the asphalt-to-fly-ash interface.

It is important to note that all of these tests were run when the fly ash had aged only two hours. As the fly ash cures and increases in strength the mechanical interlocking will also increase. A cone shaped failure surface is formed in the asphalt (similar to that caused by the removal of a bolt from hardened concrete). This effect is illustrated by the original shear tests, in which the fly ash was allowed to cure for seven days. The results of several tests can be seen in Fig. 5.15.

Because this report focuses on the repair of wet asphalt a second series of shear strength tests were run (the results of which are not shown) to see if soaking the asphalt for a long period of time diminished the strength of the fly ash/asphalt bond. One set of asphalt cylinders was submerged in water for 24 hours and then filled with a fly ash mixture. Another set was moistened with water and then immediately filled with the same fly ash mixture. Essentially no difference was found in the shear strengths at the interface.

5.5.6 Plastic Shrinkage and Peak Exotherm

The results of the DuPont plastic shrinkage test can be seen in Fig. 5.16. Three different fly ash-to-sand ratios were examined in the test along with the results of the introduction of polypropylene fibers. Note that both shrinkage (shown as negative strain) and exotherm are plotted versus the logarithm of time. The peak exotherm occurred, virtually without exception, at about 14 minutes after the water contacted the fly ash. It would seem, therefore, that the timing of the peak exotherm is virtually independent of the amount of sand which is added. The temperature of the peak exotherm, however, is not independent. Figure 5.16 not only shows that the higher peak exotherms occur with higher concentrations of fly ash but it also shows the dramatic difference in temperature for the various concentrations. It has been

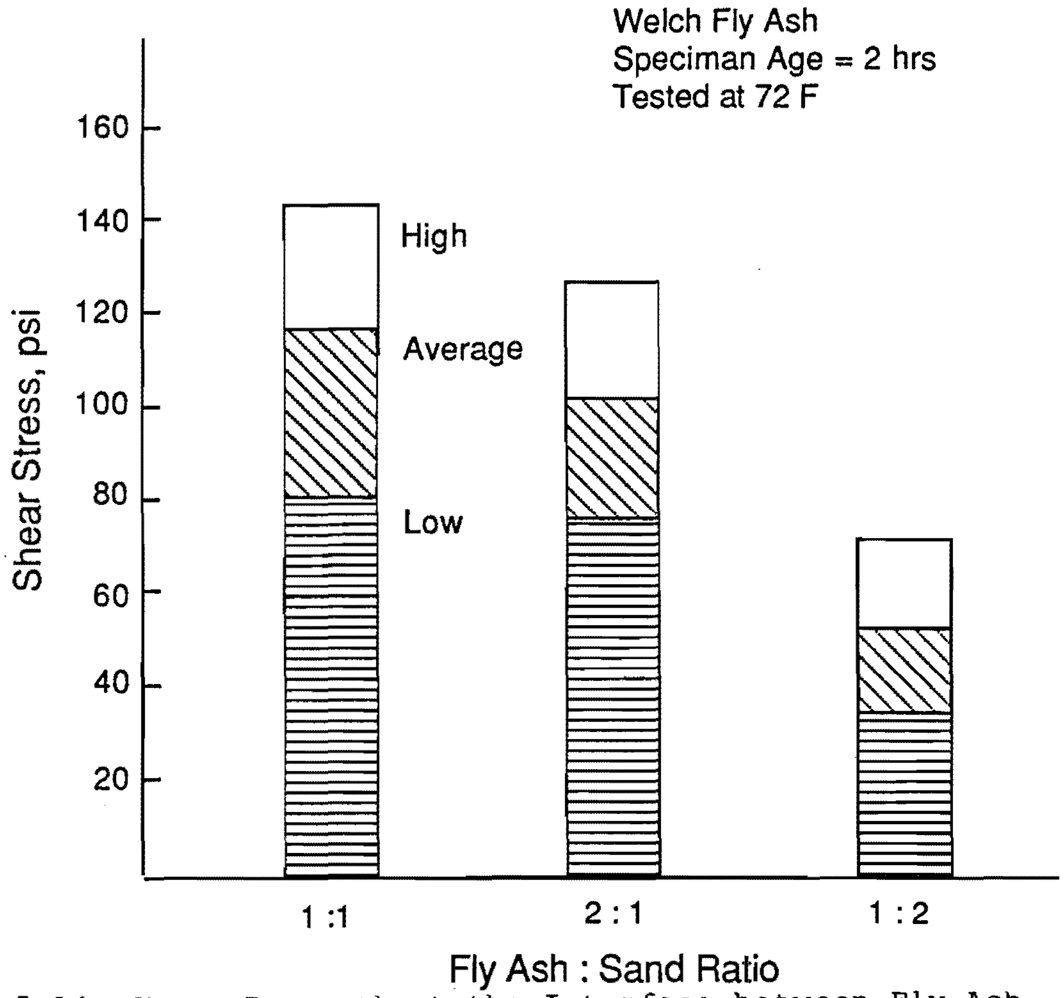


Fig. 5.14 Shear Strength at the Interface between Fly Ash and Asphalt Concrete.

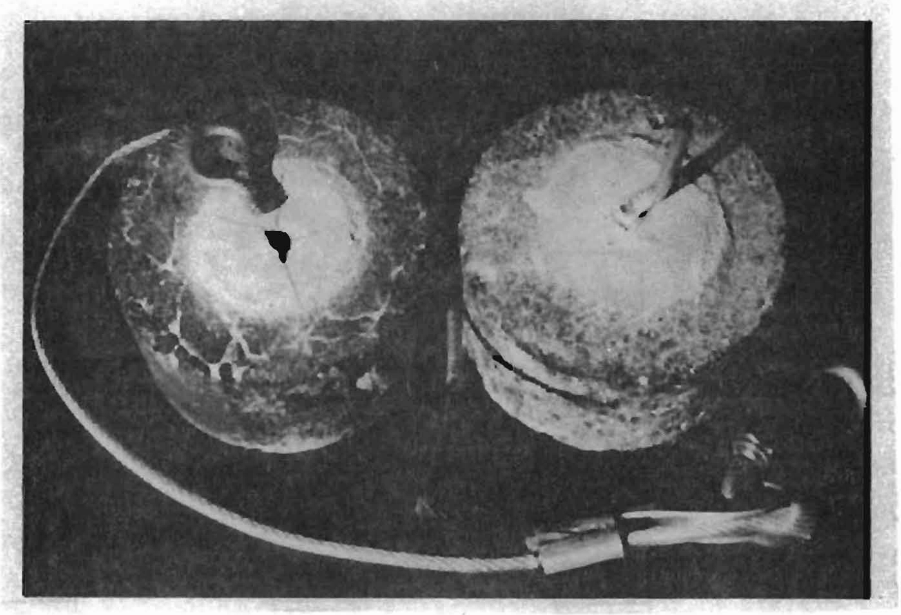


Fig. 5.15 Results of shear strength test for fly ash cured 7 days.

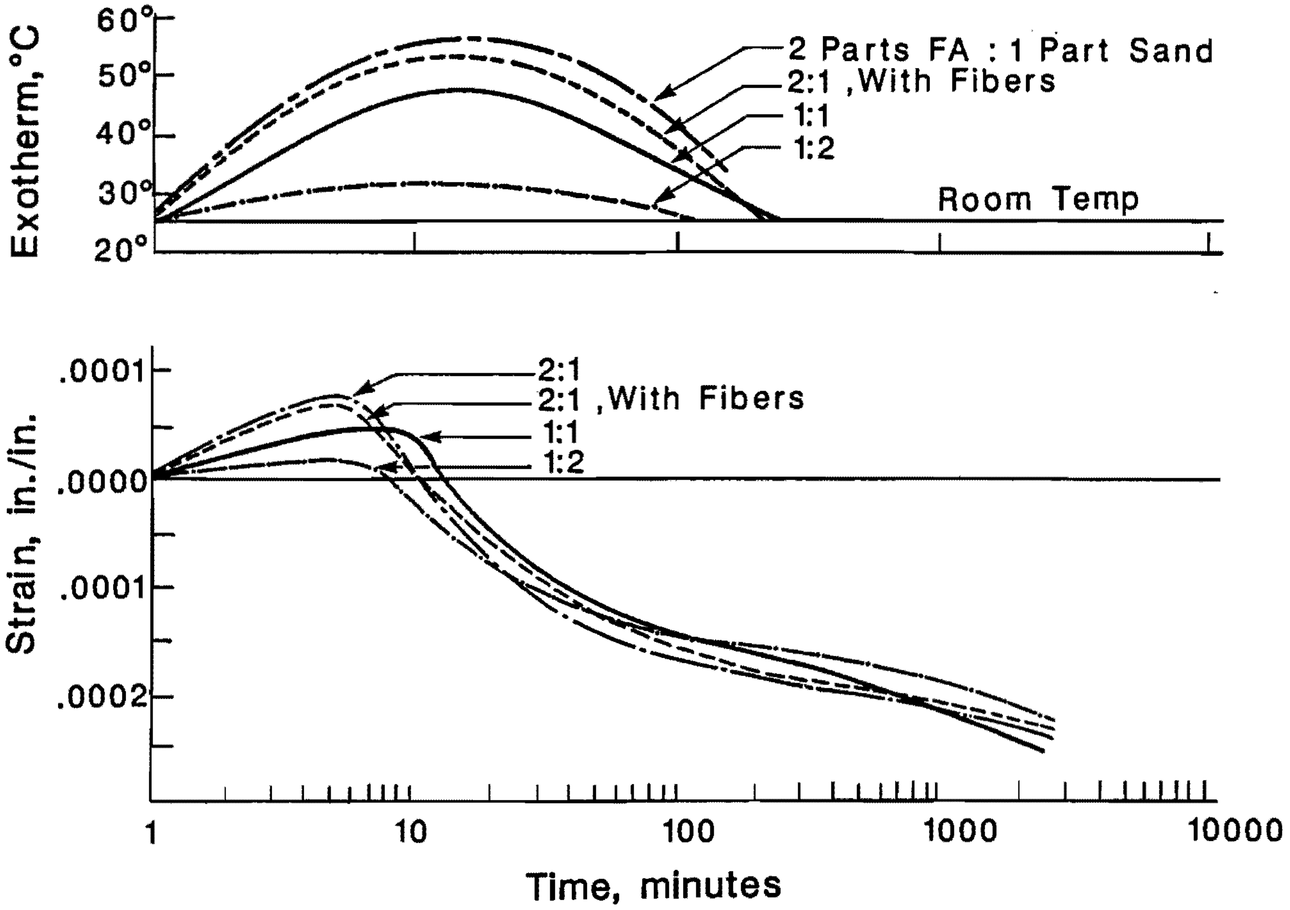


Fig. 5.16 DuPont Method of Plastic Shrinkage Test using Welch Fly Ash.

shown previously that cooling the fly ash as it is curing will increase the ultimate strength. This is reasonable since the same is true for portland cement concrete. Therefore, when higher concentrations of fly ash are used when temperatures are above 72^{O}F it is advisable to place wet burlap bags over the freshly poured road repairs for a period of time. The lower graph shows that the shrinkage of fly ash mortar falls mainly within a narrow range regardless of how much sand is added. Nevertheless, there are some surprises. First of all, the 1:1 ratio definitely showed greater shrinkage characteristics with the passage of time than any of the other mortars. Not only was the amount of shrinkage greater at the end of the test, but the slope of the curve was steeper. This small difference, however, could be due to scatter in the data. Perhaps this explains why in the Louisiana research fly ash concrete with the 1:1 ratio did not perform as well on large road repairs as did mortars with other ratios. The shrinkage problem becomes more pronounced in large repairs and furthermore the other mortar ratios contained coarse aggregate, which reduced their shrinkage problem even further. The second surprise came when it was found that the introduction of fibers had almost no effect on shrinkage reduction. As can be seen in Fig. 5.16 the curve for the 2:1 ratio without fibers coincides closely with the curve for the 2:1 ratio with fibers. The use of polypropylene fibers will be examined more closely in the next section.

5.5.7 Fly Ash Additives

5.5.7.1 Polypropylene Fibers

The effect of polypropylene fibers in shrinkage was examined in the previous section. There it was discovered that fibers do not greatly reduce the shrinkage of fly ash mortar. In this section the effect of fibers on compression, flexure, and load-deflection is examined. In particular, the change of behavior after failure has taken place will be discussed. Fibers were added in the prescribed concentration of 1.6 lb/cu. yd. (0.951 g/liter). Unlike the other materials discussed thus far, fibers must be measured by weight rather than by volume because they are subject to settlement.

Polypropylene fibers have almost no effect on the ultimate compressive stress of fly ash concrete. After many tests incorporating different ratios of fly ash, sand, and coarse aggregate, only a slight increase in compression strength was found to occur with the use of fibers. The most important effect of fibers, however, occurs after failure has taken place. Figure 5.17 shows the sudden disintegration of a fly ash cylinder without fibers compared to that of an identical cylinder which contained fibers. This important difference implies that a road repair containing fibers will probably have a longer lifespan after cracking occurs than one without fibers. This gives road repair crews an extended period of time to replace the repair without jeopardizing the safety of highway traffic.

Figure 5.18 shows the results of the load-deflection test in which numerous beams were made with and without fibers. Except for this difference the beams were

Fig. 5.17 The effect of polypropylene fibers is most significant after failure has taken place.

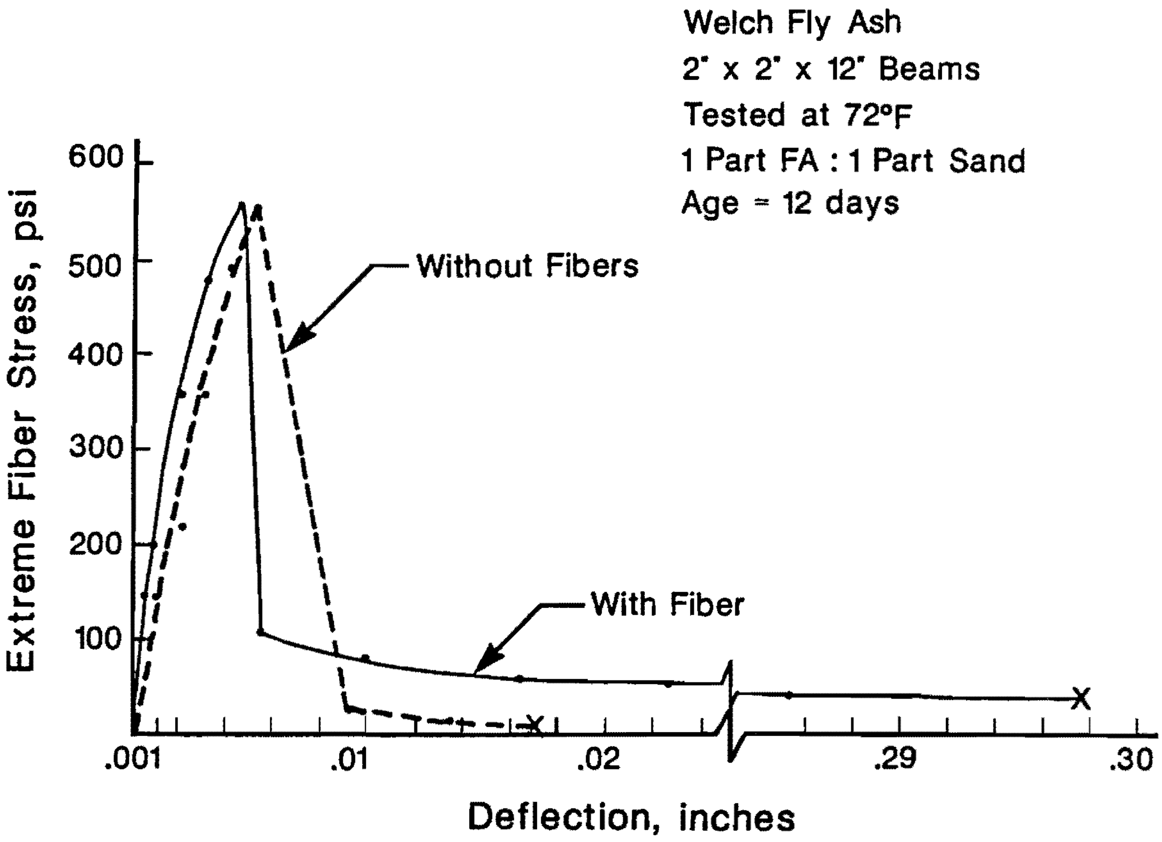


Fig. 5.18 Load-Deflection Test incorporating the use of Polypropylene Fibers.

identical and were tested under identical conditions. As can be seen in the graph the ultimate flexural strength for both sets of beams is the same. Comparing these results with those of shrinkage and compression it can be said in general that fibers do very little to enhance the characteristics of fly ash specimens before failure occurs. Referring again to Fig. 5.18, however, it appears that fibers offer a definite advantage after failure has taken place. After failure the beam containing fibers was capable of deflecting over 10 times further while sustaining almost five times the load as compared to the beam without fibers. As with compression, the importance of this advantage is that it will most likely result in a longer repair life. This becomes even more important in light of the fact that flexure is probably one of the major failure mechanisms of fly ash concrete in asphalt road repair.

5.5.7.2 Iron Oxide Coloring Agent

Normally, fly ash has a distinctive brown color when it is mixed with sand and aggregate. Figure 5.19 shows the relative colors of fly ash mortar (1 part fly ash: 1 part sand: no aggregate) when mixed with 0.0 percent, 0.2 percent, and 1.0 percent iron oxide by weight. These can be compared with the asphalt concrete cylinder on the far right. Since the brown color of fly ash eventually blends with the color of asphalt (the rate depends on the amount of traffic) adding 1.0 percent iron oxide by weight should be more than sufficient to remove the distinctive brown color. It should be noted that almost no color change occurs in the dry fly ash until immediately after water is added. Furthermore, since

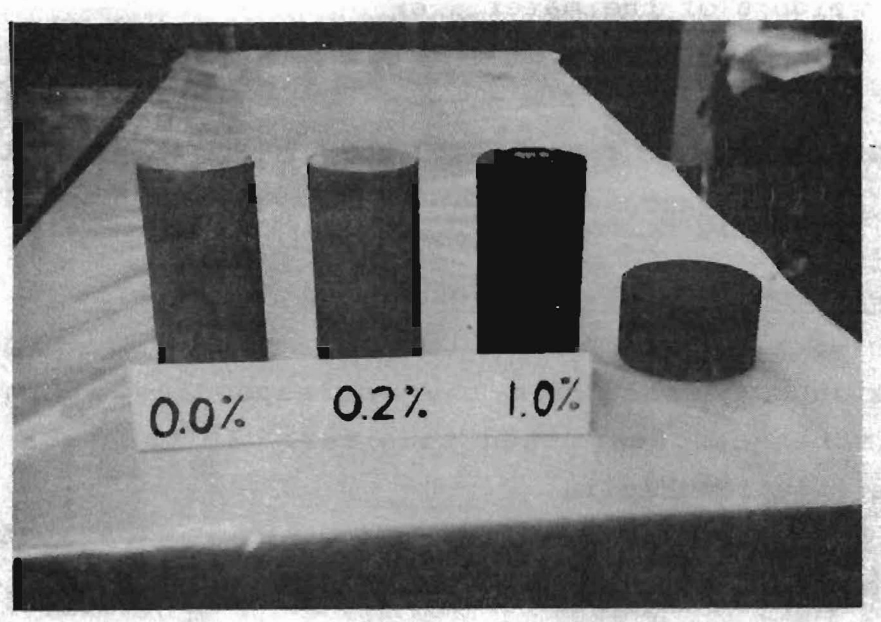


Fig. 5.19 Fly ash mixed with various ratios (by weight) of iron oxide compared to the cylinder of asphalt concrete on the right.

almost all other ratios in this report are given in terms of volume, 1 percent by weight converts to about 2 percent by volume when both iron oxide and fly ash mortar are loosely packed. This is based on the approximate dry specific weights of the materials:

fly ash only - 84.7 pct (1.36 g/ml);
1 part fly ash: 1 part sand - 99.2 pct (1.59 g/ml);
and iron oxide - 47.2 pct (.756 g/ml).

5.5.8 Relationship Between Flexure and Compression

Table 5.4 shows a summary of most of the ultimate compression stresses with the corresponding ultimate bending stresses determined thus far. In the 1983 ACI code, the relationship is

$$fr = 7.5 \quad f'c \qquad (9\text{-}9)$$

The average of the coefficients shown in the last column of Table 5.4 is 7.3 and the standard deviation is 1.3. Therefore, about 70 percent of the data falls between 6.0 and 8.6. This initial investigation indicates not only that there may be a relationship between the ultimate compression stress and the modulus of rupture, but the optimum coefficient may very well be the same as that used by the ACI code. This relationship indicates that those fly ash mixes which are stronger in compression will most likely be stronger in flexure also.

Table 5.4 Coefficients relating ultimate compression stress to extreme fiber stress in bending.

Fly Ash Source	FA : S : CA, by Volume	W : FA, by Volume	f'c ,psi	Bending Stress fr,psi	$\frac{fr}{\sqrt{f'c}}$
Deely	2 : 1 : 0	.31	2600	410	8.04
Deely	1 : 1 : 0	.31	2700	470	9.04
Deely	1 : 2 : 0	.41	900	220	7.33
Deely	1 : 0 : 0	.20	1300	190	5.27
Welch	1 : 0 : 0	.19	4000	420	6.64
Welch	1 : 1 : 0	.31	5200	525	7.28

Average 7.27
Standard Deviation 1.27

5.6 Investigation of Fly Ash, Sand and Aggregate

5.6.1 Potential Failure Mechanisms of Fly Ash Road Repairs

It is important to examine some of the problems which can be anticipated using fly ash in the repair of wet asphalt. Some of the potential modes of failure which need to be considered are as follows:

1. Compression. It is possible for the ultimate compressive stress of the fly ash to be exceeded, resulting in the crushing of the material. This characteristic is examined throughout the entire report because it is considered to be a good indicator of fly ash potential.
2. Flexure. Because of the brittle nature of a fly ash road repair the fly ash cannot accommodate significant movements of adjacent materials. Chances are good that with time the fly ash repair will be supported at several localized points and will thus be subjected to some flexural stresses. Since many road repairs have a relatively shallow depth, flexure may well be the most common failure mode for this type of material. Based on the apparent relationship between compression and flexure discussed in the previous section, it is assumed that those materials which are strongest in compression are also strongest in flexure. Although this assumption requires more research, it is certainly reasonable and will enable a greater diversity of variables to be examined since compression tests can be made fairly readily.

3. Shrinkage. This type of failure is of great importance and it was discussed in section 5.5.6. The introduction of aggregate should reduce the amount of shrinkage and therefore it is not examined in this section.
4. Freeze/Thaw. Fly ash is a brittle material, and the stiffening of adjacent materials during freezing should improve the longevity of the repair. During thawing, however, subtle movements of the asphalt may induce stresses in the bond between fly ash and asphalt or it may induce flexural stresses if the movement occurs beneath the fly ash. This problem was not examined in the lab and may require further research if it appears to be significant.
5. Shear bond. The bond between fly ash and asphalt was examined in section 5.5.5 and it was found that a correlation between the bond strength and sand concentration does indeed exist. The effect that gravel has on this property might be an interesting area for further research. Since it is the mortar which is primarily in direct contact with the asphalt there probably will be almost no difference in bond strength due to the introduction of gravel.
6. Fatigue. Fatigue failures often occur when rigid materials are subjected to repeated loads. Because fly ash is very brittle it will have difficulty absorbing the energy produced by repeated loads. This type of failure was not explored in this report because fly ash is for temporary repairs, and fatigue is not as important.
7. Hydraulics. When water is able to seep between the fly ash and the supporting material the potential for

a powerful hydraulic effect exists as loads continue to be applied to the fly ash. Since water is virtually incompressible the pressure due to traffic may break the bond between the fly ash and the asphalt until the entire road repair is loose. The strong bond which exists between fly ash and asphalt, coupled with the fact that fresh fly ash requires water to harden, should be enough to make fly ash as good a material for coping with this problem as any other currently being used.

In general, fly ash repair failures will probably occur through one or more of these mechanisms or perhaps through some combination. Since different ratios of fly ash, sand, and aggregate may fail by different modes, it would be advantageous to study each of these modes in depth. Such a study is not possible within the scope of this report, however, and so the following assumptions are made at this point:

(1) The most common type of failure in a fly ash road repair is a flexural failure.

(2) Those combinations of fly ash, sand, and aggregate which produce the strongest compressive strengths will also produce the greatest resistance to flexural, shear bond, and fatigue types of failure.

5.6.2 Compression Tests

Throughout the remaining research, 3/4-in. (19.05- mm) coarse aggregate was used exclusively except where specifically stated otherwise. Later, the use of pea gravel was examined as a potential replacement for coarse aggregate when it is not readily available.

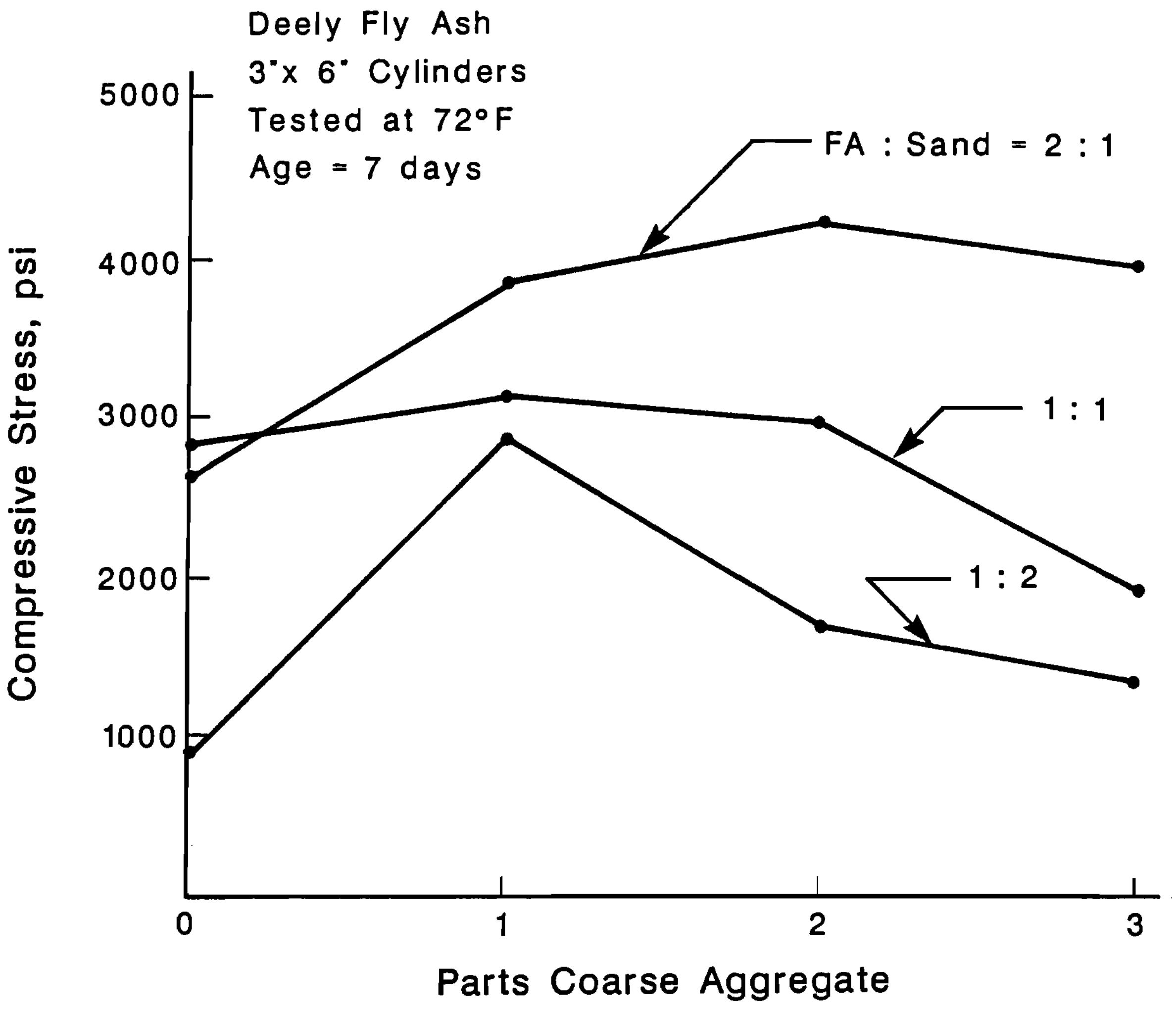


Fig. 5.20 Compression strength of Deely Fly Ash when aggregate is mixed with mortar according to Table 4.2.

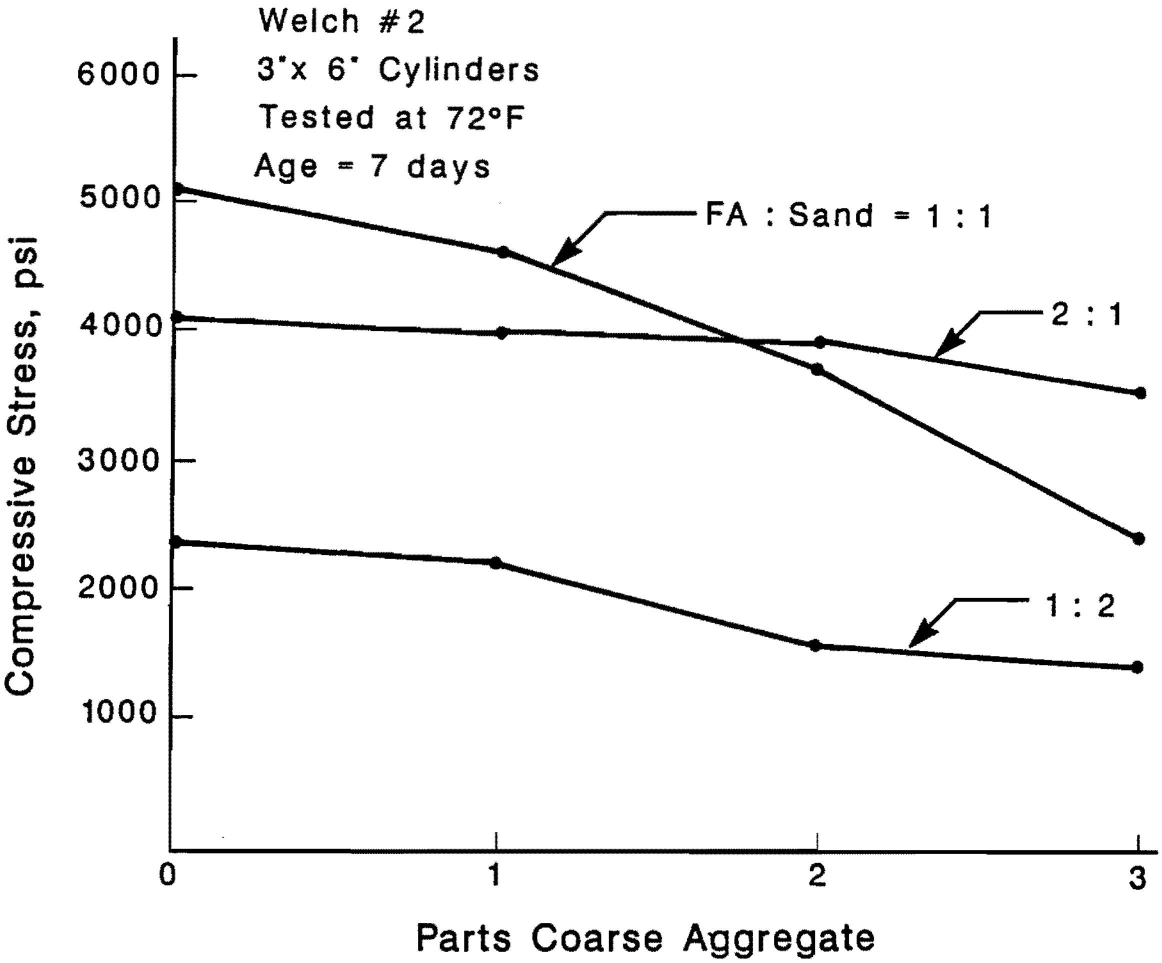


Fig. 5.21 Compression strength of Welch shipment #2 Fly Ash when aggregate is mixed with mortar according to Table 4.2.

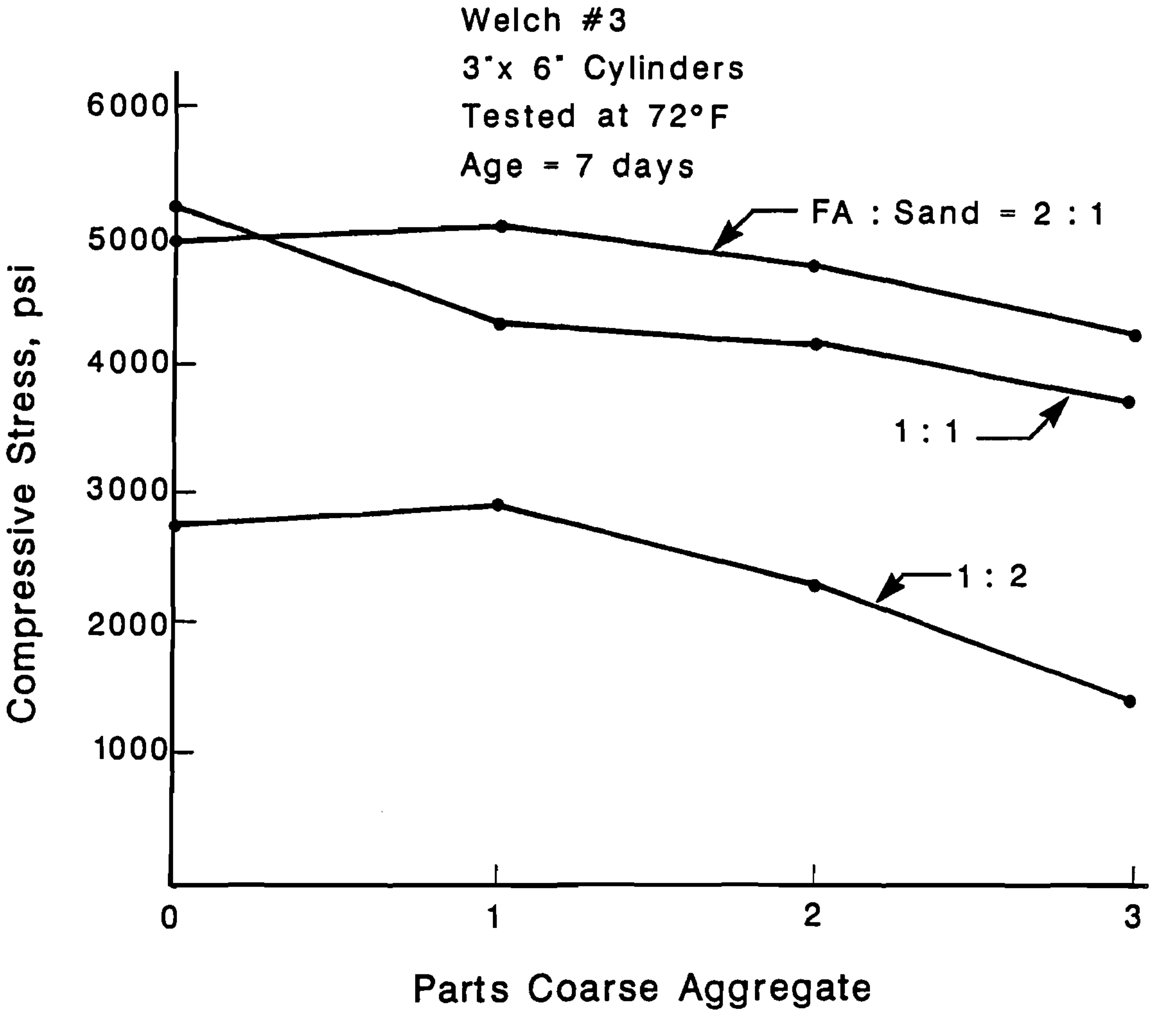


Fig. 5.22 Compression strength of Welch shipment #3 Fly Ash when aggregate is mixed with mortar according to Table 4.2.

Figures 5.20 through 5.22 show the results of many compression tests (each data point represents the average of three cylinder tests) involving different ratios of fly ash, sand, and coarse aggregate. Each figure represents a specific kind of fly ash and each line represents a specific ratio of fly ash to sand. By moving horizontally from left to right along the graph one can see the effect of increasing the proportion of coarse aggregate in each mix.

One of the first obvious conclusions that can be made from observing all three figures together is that using a mortar of one part fly ash to two parts sand will result in a very weak final product regardless of the kind of fly ash used or the amount of aggregate added. This is important because the natural tendency would be to mix the fly ash initially in the same manner as portland cement, roughly one part fly ash, two parts sand, and three parts aggregate; this procedure was used extensively in the Louisiana studies (5). As can be seen by the data point in the lower right hand corner of all three of the graphs such a combination results in a very weak material. As has already been stated, this combination is weak in compression and it is likely that it will be weak in flexure also.

A second generalization that might be made from these figures is that the mortar consisting of two parts fly ash and one part sand does not seem very sensitive to the amount of coarse aggregate which is added. In other words, when this mortar is used there can be a large amount of aggregate added with only a modest reduction in strength (the Deely fly ash actually increased in strength). This is significant because, as it has already been mentioned, using a fly ash which contains some aggregate may be advantageous. If aggregate is desired, then these tests indicate that the proportions of two parts fly ash, one part sand, and one part fly ash, one part sand, result in the strongest mixtures possible regardless of the kind of fly ash used.

The third observation based on these figures is that when Welch fly ash is chosen, the strongest mixture possible is the ratio of one part fly ash, one part sand, and no aggregate. The shipments of fly ash from the Welch plant consistently had an ultimate compression strength at one week of over 5000 psi when they were mixed according to these proportions. This result indicates that fly ash concrete is a potential candidate for other uses in addition to highway road repairs. From Fig 5.14 it can be seen that this same ratio of ingredients also produced the strongest bond to the asphalt surface. Since there is a good chance that Welch fly ash will ultimately be recommended this mixture ought to be kept in mind.

5.6.3 Optimal Water-to-Fly Ash Ratio

It is understood that road repair crews do not have the facilities or the time (particularly in wet weather) to make careful measurements of water content. For this reason it is important to ascertain the effects on the fly ash if too much or too little water is added. Figure 5.23 shows the different fly ash mortars considered thus far in which two parts of aggregate are used. It is important to note that the low water-to-fly ash ratios produce a very dry mix and the high values produce a very wet mix. It would be unusual for a repair crew to mix in an amount of water outside of the ranges which are shown.

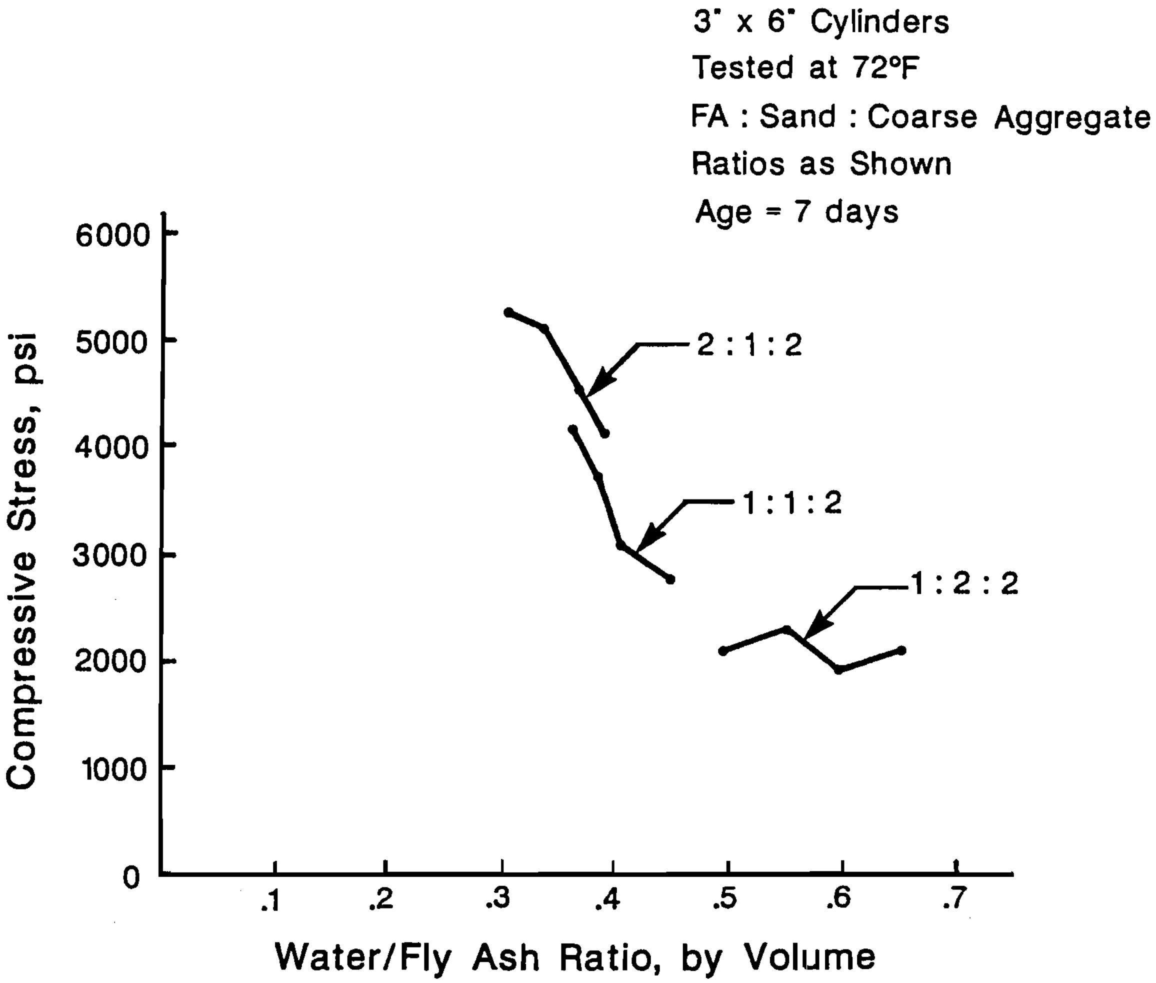


Fig. 5.23 Optimal Water to Fly Ash Ratios for different combinations of Fly Ash Sand and Coarse Aggregate.

One of the most obvious conclusions from this graph is the tremendous sensitivity exhibited by some of the mixtures. It appears that adding a small amount of excess water has the potential of reducing the ultimate strength by over 1000 psi (over 25% of the original strength) in some cases. This leads to the question as to whether or not fly ash really needs to have the consistency and workability of "typical" wet concrete. Since there may not be a need for fly ash mixes between narrow openings between rebars or flow into small voids, perhaps drier mixes could be used. Certainly one of the advantages of this is that the fly ash would harden more rapidly. The main disadvantage is that if too little water is added then mixing may be incomplete when the hardening takes place and a dramatic loss in strength will occur. Another important feature shown in Fig. 5.23 is that when the stronger mixtures are used there is a good chance that they have adequate reserve strength even if a great amount of excess water is used. In other words, if the 2:1:2 ratio is selected and too much water is added, the chances are good that the resulting f'c of 4000 psi will provide adequate strength. In fact, this graph shows clearly that the mortar containing two parts fly ash to one part sand is almost twice as strong even in its wet condition as the mortar containing one part fly ash to two parts sand in its dry condition.

5.7 Final Tests

The research in the previous section indicates that when Welch fly ash is used the best ratio of ingredients (by volume) is one part fly ash, one part sand, and no aggregate. The purpose of this section is to examine the parameters of this mixture in more detail before making final recommendations.

5.7.1 Increase of Strength with Time

One of the most important aspects of fly ash in this research study is the fact that it has the ability to harden very rapidly. Figures 5.24 and 5.25 show the rapid rate at which the fly ash mix acquires strength. Figure 5.24 shows that within 15 minutes there is easily enough strength to support the weight of a car or truck. Figure 5.25 shows that within 24 hours over 50 percent of the ultimate 28-day strength has already been achieved. Although this rate may be slowed somewhat during cooler temperatures, the trade-off is that higher ultimate strengths will ultimately be achieved. Exploring various methods of controlling this rate of hardening may be helpful in view of the fact that new problems are generated by rapid setting materials such as incomplete mixing and the inability to clean equipment thoroughly.

5.7.2 Elasticity in Compression

The stress versus strain curve for the 28-day-old fly ash mixture is shown in Fig. 5.26. Young's modulus was calculated by the secant method using values up to modulus of elasticity, therefore, is approximately 4.6 x 10^6 psi at 28 days. This result again underscores the very stiff nature of this material. It still must be determined whether the great difference in stiffness between fly ash and asphalt will cause any significant problems.

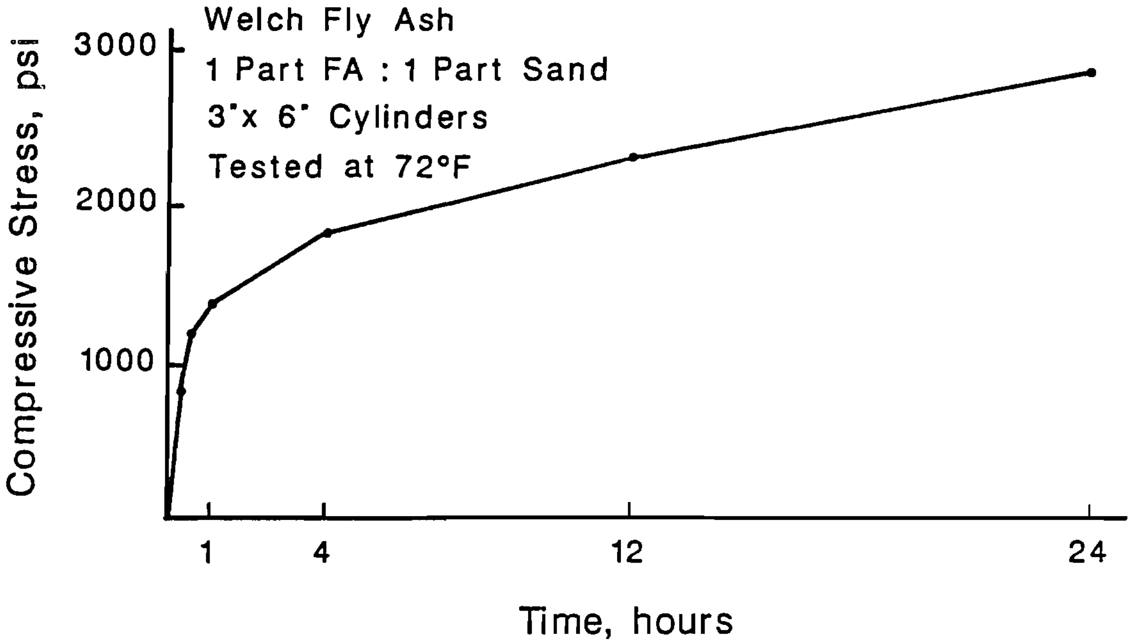


Fig. 5.24 Strength with Time Curve for Fly Ash Mortar (24 hours).

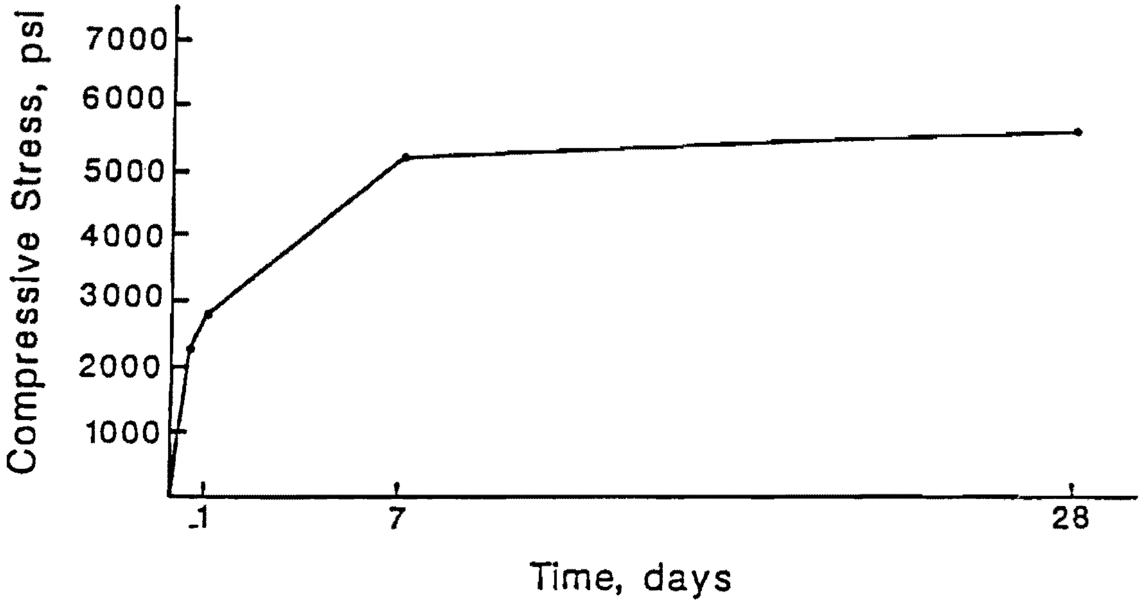


Fig. 5.25 Strength with Time Curve for Fly Ash Mortar (28 days).

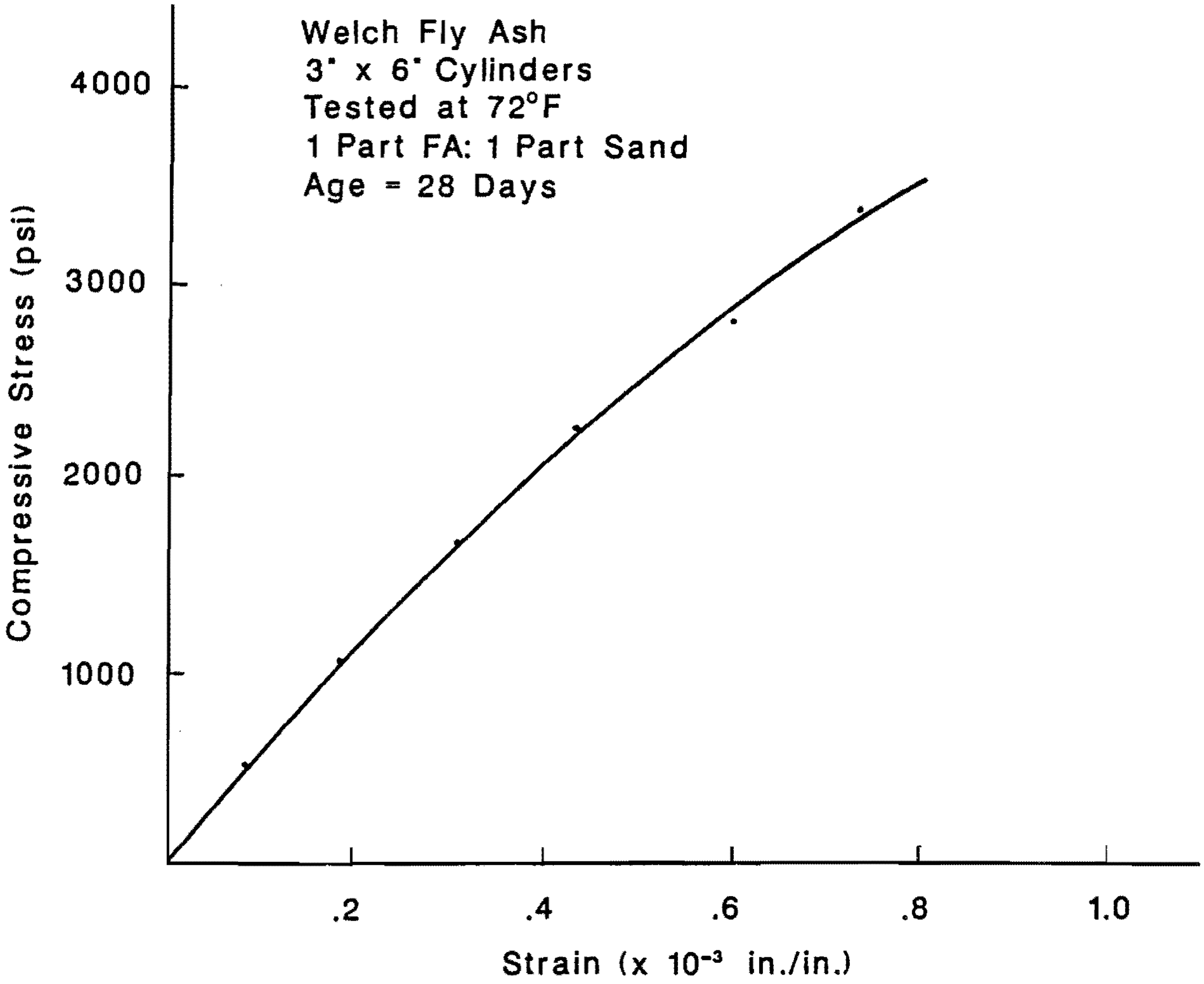


Fig. 5.26 Elasticity in Compression of Fly Ash Concrete.

5.7.3 Comparison of Fly Ash from Different Sources

Although some comparisons of different kinds of fly ash have already been made, several other kinds of self-hardening fly ash were obtained, creating the possibility of making comparisons over a broader range. The two additional types of fly ash are 1) Parish from Thompsons, Tx., and 2) Rodemaker from Boyce, La. Figure 5.27 shows the 24-hour strengths of these materials, which can be assumed to be a little more than half of the ultimate 28-day strength. As was discovered earlier, the Welch fly ash from Cason, Tx. consistently exhibits much higher strengths than those types of fly ash taken from other sources. For this reason, Welch fly ash will be used in more field tests than other kinds of fly ash.

5.7.4 Optimum Water-to-Fly Ash Ratio

Figure 5.28 shows the sensitivity to water content that the one part fly ash to one part sand mix has when it is 24 hours old. As was seen earlier the strength at 24 hours is probably close to one half the ultimate strength at 28 days. The most significant aspect shown in this figure is that it suggests the Welch fly ash, when mixed in these proportions, is not very sensitive to water content. Since the recommended water to fly ash ratio is 0.31 (by volume), it can be seen that much more water could be added with apparently no detrimental effects on compression strength. Since there is a good chance that excess water may cause other problems (such as shrinkage) an effort should still be made to keep the water content close to the recommended value. As before, the initial low value on the far left is attributed to not enough

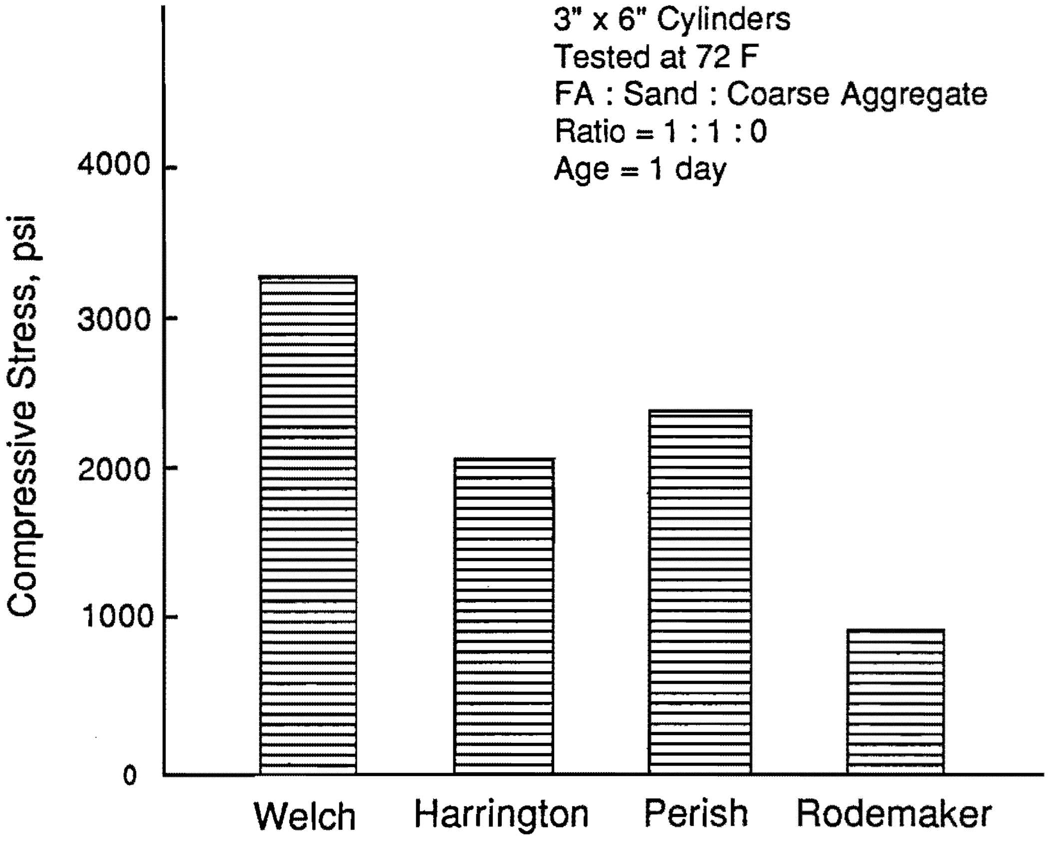


Fig. 5.27 Comparison of Fly Ash taken from different power plants.

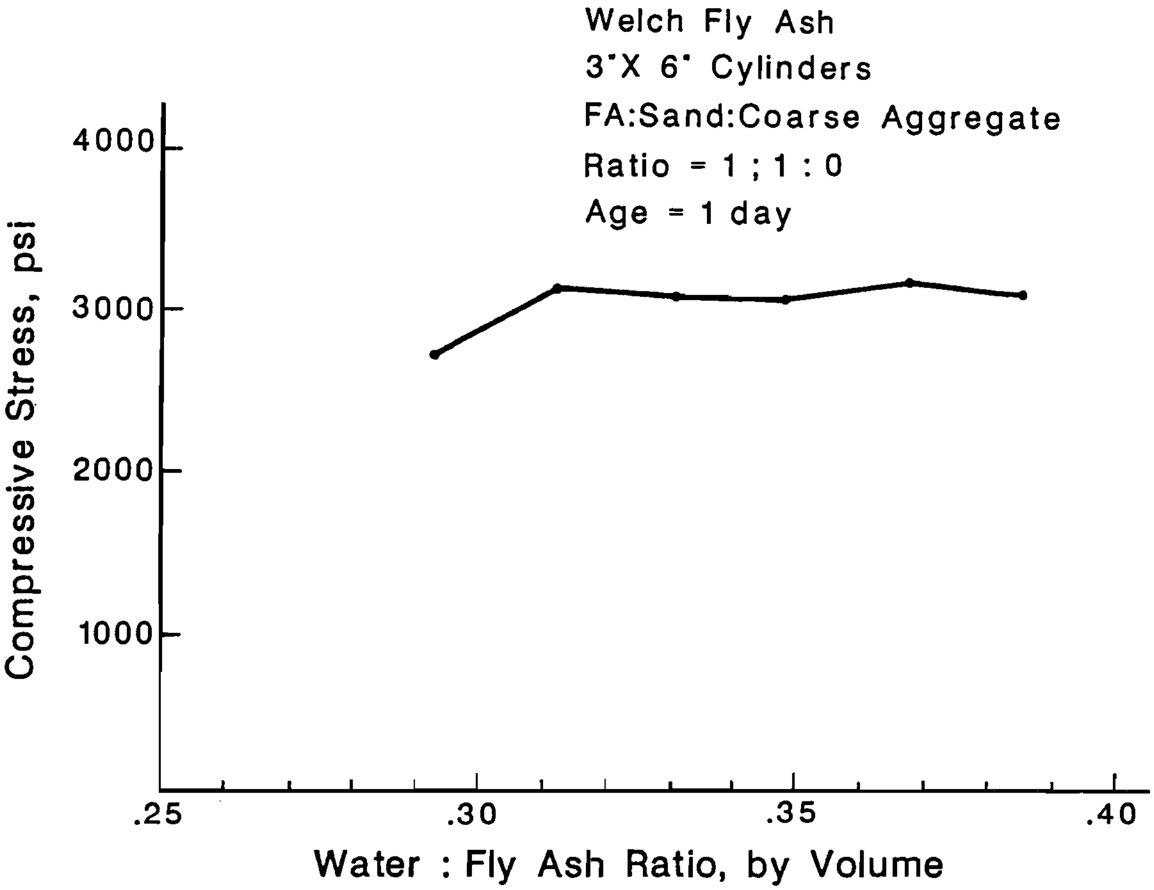


Fig. 5.28 Optimal Curve for Welch Fly Ash at 24 Hours.

water in the mix, which meant that some of the fly ash never came in contact with water.

CHAPTER 6

FIELD TEST PROCEDURES

6.1 Background

Using information acquired in the laboratory numerous methods were developed so that certain theories could be further explored in the field. Maintaining accurate records of the proportions of ingredients and other variables was essential to drawing proper conclusions. For this reason, the methods used in the field are discussed here in detail. In particular, this chapter contains a list of the recorded variables, mixing procedures, and the means by which repairs were compared.

6.2 Method of Calculations

To keep accurate records of variables such as water content, calculations often had to be made in the field. A method was developed using Table 4.2 so that this procedure could be done as simply as possible. Two different examples are given illustrating field calculations (1) when the dry materials are premixed in the lab and (2) when they are mixed in the field. The ratios given in Table 4.2 are based upon all materials being loosely compacted.

6.2.1 Sample Calculations When Using Premixed Dry Materials

Typical road repairs come in various shapes and often it is difficult to estimate the volume of material required to make them. The method which consistently gave the best results was the following:

1) Estimate the area of the hole at the road surface.
2) Estimate the area at the base of the hole.
3) Average the two areas and multiply by the depth.

Thus, for a 9-in. (22.9-cm) deep hole with an area at the road surface of 500 square inches (3226 sq. cm.) and an area at the base of 300 square inches (1935 sq. cm.) the estimated total volume would be:

$$9\ (500 + 300)/2 = 3600 \text{ cu. in. } (13.4 \text{ gal.})$$

To fill the hole with a mix containing two parts fly ash, one part sand, and two parts aggregate (2:1:2) the dry ingredients premixed using these ratios would be brought to the site and 3600 cu. in. removed from the container. This should be sufficient since the volume of dry ingredients changes only a small amount when water is added. Next, the volume of water is calculated by referring to the second column in the row containing the 2:1:2 ratio of Table 4.2. Since the total volume is 3600 cu. in. the amount of water needed in our example is:

$$\text{Water Volume} = .16 \times 3600 = 576 \text{ cubic inches } (2.1 \text{ gal.})$$

6.2.2 Sample Calculations When Dry Materials are not Premixed

Assume that the same size road repair as in the previous example needs to be filled with the same ratio of ingredients except that none of the materials has been mixed prior to arriving at the test site. Using the first, third, and fourth columns of Table 4.2 the amount of each ingredient may be calculated as follows:

Sand Volume = (0.24) (3600) = 864 cu. in. (3.2 gal.)
FA, Aggregate Volume = (2) (864) = 1728 cu. in. (6.4 gal.)
Water Volume = (0.33) (1728) = 570 cu. in. (2.1 gal.)

In any case, because fly ash will harden in about four minutes, the dry ingredients ought to be mixed together (including fibers and iron oxide if it is desired) before the water is added.

6.2.3 Other Recorded Variables

Other variables were more easily determined by bringing various equipment to the test sites or by making phone calls to agencies that maintain records pertinent to the project. The variables recorded for each test site were:

1) Fly Ash Source
2) Fly Ash: Sand: Coarse Aggregate Ratio
3) Water: Fly Ash Ratio
4) Air Temperature
5) Water Temperature
6) Initial Set Time
7) Approximate Dimensions of Repair
8) Visible Condition of the Repair at Various Ages
9) Amount of Precipitation at that Age
10) Average Daily Traffic (ADT)
11) Average Speed of Traffic
12) Type of Traffic (percentage of cars or trucks)
13) Workability of Repair Material
14) Mixing Method
15) Additives to Fly Ash

Two variables which remained constant throughout the field testing were 1) the pH of the water, 6.0; and 2) the size of the coarse aggregate, 3/4-in. (19.0mm), which was used whenever aggregate was involved.

6.3 Mixing Procedures

6.3.1 Hand Mixing

6.3.1.1 Mixing Directly in the Pothole

Several methods of handmixing were used in an effort to determine a fast and simple method for placing this material. Because Welch fly ash hardens so rapidly it was decided that hand mixing ought to be seriously considered so that the potential for hardening in mixing machines could be eliminated. The method that seemed to be the most efficient by far was that of mixing the fly ash right in the pothole itself. Figures 6.1 to 6.8 show the complete procedure by which the majority of the road repairs were made. The method was found to be simple, efficient, and, most important, fast. Different hand tools were tried but the one shown in this series of photographs seemed to work particularly well. The fact that the blade is smaller than that of a hoe and also at a slight angle gave it more versatility and better mixing characteristics than most other tools. It is called a "Swoe," a trademark of the manufacturer, True Temper, Allegheny International Hardware Group, Shiremanstown, Pa. Some of the advantages of this method are that no expensive equipment needs to be transported or maintained. Working with an electric generator in wet weather conditions is not recommended. Cleaning of tools after

Fig. 6.1 The loose material is first swept from the base of the pothole.

Fig. 6.2 Measurements are taken in order to estimate the volume of material needed.

Fig. 6.3 The sides of the hole are moistened to simulate wet weather conditions.

Fig. 6.4 A measured amount of water is poured in the hole.

Fig. 6.5 A corresponding amount of premixed dry material is then added.

Fig. 6.6 The materials are thoroughly mixed with a hand tool.

Fig. 6.7 The surface is troweled to a smooth finish.

Fig. 6.8 The material is hard before the water has even evaporated from the surrounding road surface.

the repair is completed is very simple and because of the rapid setting characteristic of fly ash this is an important feature. If it appears that fly ash is beginning to harden before the water has been thoroughly mixed the material can be quickly smoothed out and troweled. Mixing directly in the pothole eliminates the danger of having the material harden in a mixer. Some of the disadvantages of this method are that it is difficult to prevent either fly ash or water from splashing out of the hole and so for research purposes the exact quantities of either material could only be approximated. Also, there may be times when it will be difficult to mix the materials thoroughly. This could be due to an exceptionally jagged surface on the interior of the hole or to high temperatures which initiate more rapid curing or simply to a repair requiring a large volume of material. For large potholes, better mixing may be obtained by making several small batches in sequence as opposed to one very large batch. As is discussed later, the cold joint between a new batch and a freshly hardened batch does not appear to be a problem.

6.3.1.2 Mixing in a Wheelbarrow

Because mixing materials in a wheelbarrow with a hoe is a fairly common practice very little needs to be said. This method has most of the advantages of the previous method and it may be that it is especially helpful for larger road repairs. Again it should be stressed that this material is not portland cement and that mixing must be done as quickly as possible once the water comes in contact with the fly ash.

6.3.1.3 Mixing in a Bucket

To alleviate the problem of splashing, several potholes were filled with material mixed in a five-gal. bucket. The procedure was simply to pour in the correct amount of water first (this is important), add the fly ash mix and stir with the "swoe" hand tool. This method worked extremely well because there was no mess, the bucket was easy to clean, and there could be certainty that the materials were mixed in proper proportions. The main limitation of this procedure is that it obviously could not be used for large repairs. Even so, many of the repairs which must be filled during wet weather will be small in size and well within the range of this procedure. Since the bucket is normally filled more than two-thirds a somewhat larger container may be desirable.

6.3.2 Machine Mixing

For very large road repairs there may be no alternative to using conventional machines to mix the material. A sufficiently, large crew should be available to place the material and to clean the machine immediately after the mixing is complete or the material will begin hardening very rapidly inside. Because the rate at which fly ash hardens is affected by temperature, special precautions may be necessary in hot weather. At the expense of decreasing strength, extra water should be added to provide more time for thorough mixing to take place. Extra water may be required whenever machine mixing is used but it is especially important when the temperature is above 75°F. In any case, the first step in any mixing operation should be to put the correct amount of water into the machine before any dry material is added. This is especially important for fly ash because, if the dry material is added before the water, the sticky nature of fly ash will prevent mixing from taking place.

6.4 Comparison of Road Repairs

Because so many variables are involved, including everything from the chemistry of the asphalt to local traffic conditions, it is somewhat difficult to make legitimate comparisons between various road repairs. For this reason, an attempt was made to place the repairs as close together on the same route whenever one variable in particular was being examined. However, there still existed differences in the sizes and shapes of the repairs being compared, but other differences could be minimized. The following chapter contains a description of most of the repairs made and a discussion comparing the repairs. The changes which occurred with time for each repair were recorded by means of visual observations and photographs.

CHAPTER 7

RESULTS - FIELD RESEARCH

7.1 Background

This chapter contains a discussion of the field tests, with particular attention given to some of the main variables previously examined. The Appendix contains photographs of the repairs along with the main characteristics of each repair. For convenience, a summary of these characteristics is given in Table 7.1, which will be referred to frequently in the discussion which follows. Other pertinent information regarding the repairs, not necessarily shown in the Appendix, is introduced in this chapter. Discussion is centered mainly on variables which are important: fly ash sources, ratio of ingredients, wet weather effects, mixing methods, geometry of repairs, and failure mechanisms.

7.2 Fly Ash Sources

Various kinds of fly ash were used in the field tests; some can be seen in Table 7.1. As expected, the fly ash which did by far the best was the type which came from the Welch plant near Cason. Other kinds of fly ash did not do nearly as well and the overall ranking of the fly ash types essentially follows the results given in Fig. 5.27. The repair with the Harrington fly ash from the plant near Amarillo (repair no. 6) showed signs of cracking much earlier but nevertheless is still intact, with no new cracks appearing. Thus, even though the Welch fly ash seemed to perform much better than the others, it is possible that other kinds of fly ash may be used for repairs which have only a small amount of traffic.

Table 7.1 Summary of Road Repairs as of January 21, 1986

Repair #	FA Source	FA: Sand: CA	Water: FA	Air Temp	Water Temp	Set Time	Dimensions	Age	Rainfall	ADT	Additives	Current Condition
2	Welch	1:2:1	.50(high)	82°F	77°F	4 mins.	21x12x5	235 days	22.1 in.	6330	None	Poor
3	Welch	2:1:3	.33	78	77	3	20"x12"x4"	227	21.0	6330	None	Excellent
4	Welch	1:2:1	.35	78	77	3	11"x11"x2	227	19.5	6330	None	Excellent
5	Welch	1:2:1	.35	96	104	3	18"x27"x6"	223	19.5	5780	None	Fair
6	Harrington	1:2:1	.48	84	73	6	27"x30"x4"	222	19.5	6330	None	Good
7	Welch	1:1:1	.25(dry)	90	73	4	18x18x2	222	19.5	6330	None	Excellent
8	Welch	1:1:1	.30(dry)	94	77	4	9x9x3	222	19.5	6330	None	Excellent
9	Welch	2:1:3	.35	95	77	4	18x7x3	222	19.5	6330	None	Excellent
11	Welch	2:1:3	.36	85	75	4	7x7x3	213	19.5	23610	None	Excellent
12	Welch	1:2:1	.36(dry)	85	75	3	9x9x3	213	19.5	23610	None	Excellent
13	Welch	1:1:1	.30(dry)	85	75	3	9x10x3	213	19.5	23610	None	Excellent
14	Welch	1:0:0	.20	85	75	5	16x10x4	213	19.5	23610	None	Fair
15	Welch	2:1:3	.36	91	81	4	12x18x3	205	19.4	4660	Fibers	Excellent
16	Welch	2:1:3	.36	91	81	4	15x21x3	205	19.4	4660	None	Very Good
17	Welch	1:2:1	.55	94	82	7	16x20x3	192	16.9	4340	None	Very Good
18	Welch	1:1:0	.31	95	95	4	40x14x4	188	16.9	10870	None	Good
19	Welch	1:1:0	.31	95	35	9	22x13x3	188	16.9	10870	None	Very Good
20	Welch	1:1:0	.33	92	92	3	20x20x2	154	16.2	18950	Fibers	Poor
22	Parish	1:1:0	.31	95	85	6	9"x14"x3"	154	16.2	6330	None	Fair

7.3 Ratio of Ingredients

7.3.1 Dry Ingredients

One of the surprising results is that the one part fly ash, one part sand, and no parts coarse aggregate (1:1:0) ratio of ingredients which seemed to do well in the laboratory tests did not do as well in the field. Both repair no. 18 and repair no. 20 were expected to do well but in fact turned out to be very susceptible to pitting of the surface material. In contrast to this, repairs containing an additional one part aggregate all seem to be doing very well. The importance of including coarse aggregate is in agreement with the fly ash road repair studies conducted in Louisiana (5). Another type of mix which was expected to do well was that containing a ratio of ingredients of 2:1:3. As can be seen from Table 7.1, all of the repairs using this combination are doing very well and currently show no signs of deterioration. Except for some small hairline cracks in repairs no. 15 and no. 16, the surfaces of these repairs show no sign of pitting or flaking.

Some repairs were made using a 1:2:1 ratio because, as can be seen from Figures 5.20 to 5.22, this generally gives the highest laboratory strengths. In general this combination did well, although the results were inconsistent. Repair no. 2, for example is showing definite signs of decomposing.

Repairs no. 11, no. 12, no. 13 and no. 14 all represent different ratios of ingredients. These repairs can be directly compared with one another because they are all within about 15 ft. (4.57 m) of each other. Currently, the only one which is showing real signs of deterioration is no. 14, which contains pure fly ash without any sand or aggregate. Observations will continue to be made of all the road repairs.

Overall, the field tests indicate that either a 1:1:0 or 2:1:3 ratio of ingredients should be used for repairs.

7.3.2 Sensitivity to Water Content

Several of the values listed under the column showing water-to-fly-ash ratios in Table 7.1 indicate "dry". It should be pointed out that this does not mean the mixture was unworkable but only that it contains substantially less water than what is recommended in Table 4.1 and that it is a thicker consistency than what is normally considered "wet concrete." It is apparent that this decrease in water content has a remarkable effect on the outcome of the final product. For this reason it is emphasized that, although Table 4.1 gives the descriptions of water content used frequently in this project, the preferred method in using this material is to add as little water as possible. Obtaining a workability so thick that the fly ash mix cannot be poured into the hole but must actually be "packed" in may ultimately be the way this material should be used.

7.3.3 Additives

The only additive considered in the field tests was the polypropylene fibers. Since one of the objectives of this study was to keep costs to an absolute minimum, it was felt that using many expensive additives was not in the best interest of this project.

The fibers were directly compared in repairs no. 15 and no. 16. Since these repairs were approximately of equal size and on the same roadway they should give a good indication of the effectiveness of fibers. Currently the repair containing fibers is in slightly better condition, showing almost no surface wear and fewer hairline cracks. Laboratory tests indicated that fibers had very little effect before cracking occurred but that they caused a dramatic improvement after the first crack occurred. It appears from the field tests that fibers do improve the quality of the road repair and help keep the repaired surface from pitting.

7.4 Effect of Wet Weather Conditions

7.4.1 Adhesion to Wet Asphalt

Virtually all of the repairs were made by first moistening the walls of the asphalt as described in chapter 6. Some of the repairs were purposely made without moistening the walls so that a comparison could be made. Repairs no. 11, no. 12 and no. 13 did not have moistened walls and repairs no. 15, no. 4 and no. 7 all did. Notice that these six repairs essentially cover the different types of ingredient ratios and that all six repairs are still in excellent condition. The important conclusion is that moisture apparently has no effect on decreasing the bond which fly ash has with asphalt. This is important because as has already been discussed it is the strong bond which fly ash is capable of developing with asphalt that helps make it a valuable road repair material.

7.4.2 Precipitation

Table 7.1 shows the amount of rainfall which has fallen on the various potholes since the repairs were made. As can be seen there does not seem to be any correlation between the condition of the repair and the subsequent precipitation. On the contrary, those repairs which have not been subjected to extensive rainfall do not as a whole appear to be in any better condition than those which have. It should be noted that there has been no evidence indicating that any of the repairs were subjected to standing water except during the rainstorms themselves.

7.4.3 Temperature

A series of repairs were made under virtually identical conditions in which only the temperatures of materials were allowed to vary. Repair no. 18 was mixed according to the temperatures shown, while the ingredients of repair no. 19 (including dry ingredients) were refrigerated to about 33°F and placed in a thermos until the repair was made. The difference between the two repairs is fairly significant, indicating that temperature makes a difference in the quality of the repair. The important thing, however, is that fly ash works better at cool temperatures, which is typically one of the conditions existing during wet weather. Unlike some materials which require room temperature to cure properly, this test shows that fly ash will actually harden very well at near freezing temperatures. Since fly ash will also work at warm temperatures (like those experienced in most of these field tests) it begins to be apparent that this is a versatile material. This characteristic supports the use of fly ash as a highway repair material.

7.5 Comments on Mixing Methods

Of the different methods which were discussed in chapter 6, the method of mixing fly ash directly in the pothole seemed to work fairly well. At times the fly ash began to harden before it had been thoroughly mixed but in general there were no problems. Repairs no. 5 and no. 6 were filled one section at a time so that thorough mixing could be guaranteed. Naturally, this produced an interface between the wet fly ash and the freshly hardened fly ash. Interestingly enough, the crack which later appeared in repair no. 6 did not occur at an interface and apparently there is an adequate bond at the interface. This is a property which may be useful for large repairs where it is imperative to mix one section at a time.

7.6 Geometry of Road Repair

This section discusses the sizes and shapes for which fly ash repairs may be best suited. By far the most apparent factor is simply the volume of the repair itself. Those repairs which were of a relatively small volume are generally in much better condition than those which were not. Although most of the large repairs are in good condition, virtually all of the small repairs containing Welch fly ash and some aggregate are in excellent condition. One of the surprises of this study was that most of those repairs which were subjected to severe traffic conditions, namely repairs no. 11, no. 12 and no. 13, are all still in excellent condition. These repairs are all fairly small in size. The strong bond which fly ash forms with asphalt may be a major reason for this. This is because in large repairs other factors such as flexure become more pronounced and may eventually cause cracking whereas in small repairs the bond between the fly ash and the asphalt may be able to exert a greater influence on the overall behavior. If this is true, then fly ash may also be a useful material for repairing various kinds of cracks in roadways.

7.7 Failure Mechanisms

Table 7.1 introduces another type of failure which merits some attention. Several of the road repairs began to show evidence of pitting in which the repair as a whole did not fail but the surface became increasingly rough. Most of the repairs did not exhibit this problem but there was enough evidence to make it worthy of consideration. Most frequently the repairs which contained no aggregate had the greatest problem with pitting and it has already been decided that all fly ash mixes should contain at least some aggregate.

The cracking which occurred was most likely due to excessive flexural stress. Sometimes it was difficult to tell but usually the cracks appeared in a direction which was transverse to the longitudinal axis of the repair.

There was no indication in any of the repairs that fly ash was experiencing a debonding problem with the asphalt. This is important because most repair materials have difficulty making sound bond with wet asphalt concrete, especially in wet conditions.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

Conventional asphalt repair materials have been found to have difficulty making an adequate bond with wet asphalt, especially in cold weather. Various materials such as furan resin and magnesium phosphate are currently being considered for these kinds of repair. TSDHPT District 5 reports that Class C fly ash has been successfully used to repair potholes. The material hardens quickly and is said to be permanent. An additional characteristic which makes fly ash a desirable repair product is that it is very inexpensive compared with other materials now being tested.

This report begins by discussing the characteristics of fly ash as a material. Essentially fly ash is the finest part of the residue collected from fossil fuel power plants. Since the cementitious qualities of fly ash is highly dependent on the type of coal burned, various samples from different power plants were collected and tested in the laboratory and then in the field. After determining a desirable source for the fly ash, the focus of the project turned towards obtaining optimal ratios of sand, coarse aggregate, and water.

8.2 Conclusions

8.2.1 Laboratory Testing

Virtually in every test, fly ash obtained from one particular source performed better than all of the other kinds of fly ash. The fly ash obtained from the

Welch plant near Cason, Texas, achieved almost twice the compression strength and flexural strength as the ash from other sources.

Further testing showed fly ash to be an extremely fast setting (unworkable in 3 minutes at room temperature) and brittle material that is very sensitive to both temperature and water content. When mixed in correct proportions with sand and aggregate it is capable of developing high compression strength along with excellent bond to asphalt even when the asphalt is wet and cold. The inclusion of polypropylene fibers appears to be of little use until cracking occurs, when the longevity of the repair may be significantly improved.

8.2.2 Field Testing

Because fly ash is a rapid setting material, a reasonable balance had to be obtained between adding so little water that the material hardened before proper mixing could take place and so much water that the strength of the material was significantly reduced. Different mixing procedures were tried in an attempt to optimize this problem.

Contrary to some of the laboratory results, it was found that at least some aggregate must be incorporated with the fly ash for the repair to have sufficient resistance to traffic. Some of the mechanisms by which a few of the repairs appear to be failing are (1) pitting of the pothole surface and (2) cracking of the repair due to its brittle characteristics. No evidence of debonding has been exhibited by any of the repairs. The field testing consistently showed that fly ash will form an excellent bond with asphalt even during wet and cold conditions.

8.2.3 Cost

Fly ash in general is very inexpensive when compared with the cost of other repair materials. A major portion of the cost is for shipping. For this reason, it is recommended that the fly ash obtained from the Welch plant be used.

8.3 Recommendations

The following recommendations are made based on the laboratory and field studies:

1) Although all 3 types of fly ash examined in this report behaved satisfactorily (Deely, Harrington, and Welch) the fly ash obtained from the Welch plant in Cason, Texas, gave the best results.
2) Fly ash should not be used when air temperatures exceed 80^{o}F.
3) Add polypropylene fibers in the proportions of 1.6 lb/cu. yd. (.000951 g/cc) to control cracking.
4) Add iron oxide as a coloring agent in the proportions of one percent by weight or two percent by volume.
5) If at all possible, premix all of the dry ingredients before reaching the repair site, using a ratio of one part fly ash: one part sand: one part coarse aggregate (by volume). Include polypropylene fibers and iron oxide in the premix if they are to be used.
6) Fill or drain the pothole such that the water level is approximately one-fifth of the total volume.
7) Add the fly ash premix directly into the pothole and begin stirring rapidly with a hand tool.

8) Continue stirring and adding more fly ash until the mixture has a fairly stiff consistency.
9) Trowel the surface of the repair.
10) Open the repair to traffic as soon as it has hardened, usually after 15 minutes.

8.4 Future Tests

The following tests were not conducted in this report and may provide valuable insight in the further improvement of this product.

1) ASTM Penetrometer Test (C403-77) - Better understanding of the rate at which fly ash hardens could be obtained by determining the resistance fly ash has to penetration as it cures.
2) The Effect of Standing Water - This report has already shown that fly ash will cure under water; however, the long term effect that standing water may have on decomposing the repair surface has not been shown. Placing several small slabs of fly ash underwater and subjecting them to the ASTM Abrasion Resistance Test (C418-81) should give an estimate of this problem. A comparison could then be made by repeating the test using similar slabs of portland cement or any other material.
3) Interface Bond Strength between Wet Fly Ash and Freshly Hardened Fly Ash - It was suggested that wet fly ash will bond very well to freshly hardened fly ash in this report. Objective means of determining this would be valuable.
4) Workability Index - This research has shown that fly ash tends to be very sensitive to the amount of water added. Furthermore the basis by which different ratios

of fly ash, sand, and aggregate were compared was that water was added until the workability of each mix was the same. Because fly ash hardens so rapidly conventional slump tests were not applicable. For this reason the workability of each mix was based on observation. Determining an objective means instead of a subjective means of recording this would be useful if further research is conducted.

Further investigation of shrinkage effects, freeze/thaw action, and mixing methods would be valuable in determining the limiting conditions within which fly ash can be used. It may be that fly ash has a definite place among road repair materials but that it is limited to certain kinds of road conditions.

5) Asphaltic concrete is often recycled and it would be helpful to know what side effects will occur if fly ash patches have been introduced to the asphalt material. Currently it is presumed that the fly ash patch will be broken up during the recycling process and mix with the aggregate already in the asphalt.

APPENDIX

PHOTOGRAPHS OF ROAD REPAIRS

Fig. A.1 Most Recent Photograph of Repair Number 2.

FA Source - Welch	Dimensions - 21x12x5
FA:Sand:CA - 1:2:1	Age of Repair - 235 days
Water:FA - .50 (high)	Rainfall - 22.1 inches
Air Temp - 82°F	ADT - 6330
Water Temp - 77°F	Additives - None
Set Time - 4 min.	Current Condition - Severly Pitted

Fig. A.2 Most Recent Photograph of Repair Number 3.

FA Source - Welch
FA:Sand:CA - 2:1:3
Water:FA - .33
Air Temp - 78
Water Temp - 77
Set Time - 3

Dimensions - 21x12x5
Age of Repair - 227 Days
Rainfall - 21.0 in.
ADT - 6330
Additives - None
Current Condition - Excellent

Fig. A.3 Most Recent Photograph of Repair Number 4.

FA Source - Welch
FA:Sand:CA - 2:1:3
Water:FA - .35
Air Temp - 78
Water Temp - 77
Set Time - 3

Dimensions - 11x11x2
Age of Repair - 227
Rainfall - 19.5
ADT - 6330
Additives - none
Current Condition - Excellent

Fig. A.4 Most Recent Photograph of Repair Number 5.

FA Source - Welch

FA:Sand:CA - 1:2:1

Water:FA - .35

Air Temp - 96

Water Temp - 104

Set Time - 3

Dimensions - 18x27x6

Age of Repair - 223

Rainfall - 19.5

ADT - 5780

Additives - None

Current Condition - Good

Fig. A.5 Most Recent Photograph of Repair Number 6.

FA Source - Harrington
FA:Sand:CA - 1:2:1
Water:FA - .48
Air Temp - 84
Water Temp - 73
Set Time - 6

Dimensions - 27x30x4
Age of Repair - 222
Rainfall - 19.5
ADT - 6330
Additives - None
Current Condition - Cracking

Fig. A.6 Most Recent Photograph of Repair Number 7.

FA Source - Welch
FA:Sand:CA - 1:1:1
Water:FA - .25(dry)
Air Temp - 90
Water Temp - 73
Set Time - 4

Dimensions - 18x18x2
Age of Repair - 222
Rainfall - 19.5
ADT - 6330
Additives - None
Current Condition - Excellent

Fig. A.7 Most Recent Photograph of Repair Number 8.

FA Source - Welch	Dimensions - 9x9x3
FA:Sand:CA - 1:1:1	Age of Repair - 222
Water:FA - .30(dry)	Rainfall - 19.5
Air Temp - 94	ADT - 6330
Water Temp - 77	Additives - None
Set Time - 4	Current Condition - Excellent

Fig. A.8 Most Recent Photograph of Repair Number 9.

FA Source - Welch

FA:Sand:CA - 2:1:3

Water:FA - .35

Air Temp - 95

Water Temp - 77

Set Time - 4

Dimensions - 18x7x3

Age of Repair - 222

Rainfall - 19.5

ADT - 6330

Additives - None

Current Condition - Excellent

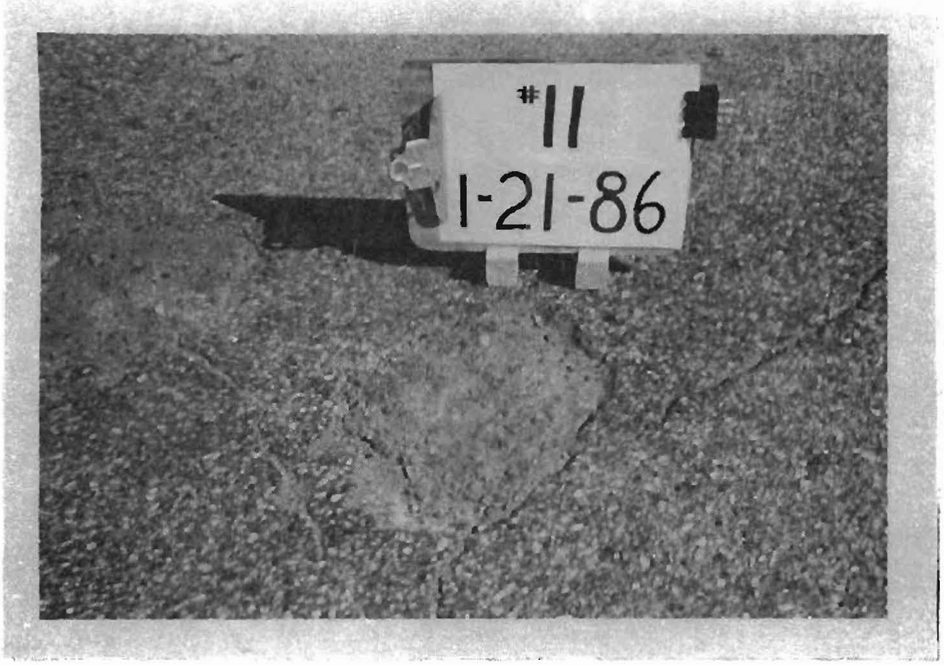


Fig. A.9 Most Recent Photograph of Repair Number 11.

FA Source - Welch
FA:Sand:CA - 2:1:3
Water:FA - .36
Air Temp - 85
Water Temp - 75
Set Time - 4

Dimensions - 7x7x3
Age of Repair - 213
Raintall - 19.5
ADT - 23610
Additives - None
Current Condition - Excellent

Fig. A.10 Most Recent Photograph of Repair Number 12.

FA Source - Welch
FA:Sand:CA - 1:2:1
Water:FA - .36(dry)
Air Temp - 85
Water Temp - 75
Set Time - 3

Dimensions - 9x9x3
Age of Repair - 213
Rainfall - 19.5
ADT - 23610
Additives - None
Current Condition - Excellent

Fig. A.11 Most Recent Photograph of Repair Number 13.

FA Source - Welch	Dimensions - 9x10x3
FA:Sand:CA - 1:1:1	Age of Repair - 213
Water:FA - .30(dry)	Rainfall - 19.5
Air Temp - 85	ADT - 23610
Water Temp - 75	Additives - None
Set Time - 3	Current Condition - Excellent

Fig. A.12 Most Recent Photograph of Repair Number 14.

FA Source - Welch
FA:Sand:CA - 1:0:0
Water:FA - .20
Air Temp - 85
Water Temp - 75
Set Time - 2

Dimensions - 16x10x4
Age of Repair - 213
Rainfall - 19.5
ADT - 23610
Additives - None
Current Condition - Very Pitted

Fig. A.13 Most Recent Photograph of Repair Number 15.

FA Source - Welch
FA:Sand:CA - 2:1:3
Water:FA - .36
Air Temp - 91
Water Temp - 81
Set Time - 4

Dimensions - 12x18x3
Age of Repair - 205
Rainfall - 19.4
ADT - 4660
Additives - Fibers
Current Condition - Excellent

Fig. A.14 Most Recent Photograph of Repair Number 16.

FA Source - Welch
FA:Sand:CA - 2:1:3
Water:FA - .36
Air Temp - 91
Water Temp - 81
Set Time - 4

Dimensions - 15x21x3
Age of Repair - 205
Rainfall - 19.4
ADT - 4660
Additives - None
Current Condition - Very Good

Fig. A.15 Most Recent Photograph of Repair Number 17.

FA Source - Welch
FA:Sand:CA - 1:2:1
Water:FA - .55
Air Temp - 94
Water Temp - 82
Set Time - 7

Dimensions - 16x20x3
Age of Repair - 192
Rainfall - 16.9
ADT - 4340
Additives - None
Current Condition - Very Good

Fig. A.18 Most Recent Photograph of Repair Number 20.

FA Source - Welch
FA:Sand:CA - 1:1:0
Water:FA - .33
Air Temp - 92
Water Temp - 92
Set Time - 3

Dimensions - 20x20x2
Age of Repair - 154
Rainfall - 16.2
ADT - 18950
Additives - Fibers
Current Condition - Pitted

Fig. A.19 Most Recent Photograph of Repair Number 22.

FA Source - Welch
FA:Sand:CA - 1:1:0
Water:FA - .33
Air Temp - 92
Water Temp - 92
Set Time - 3

Dimensions - 9x14x3
Age of Repair - 154
Rainfall - 16.2
ADT - 6330
Additives - None
Current Condition - Cracking

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