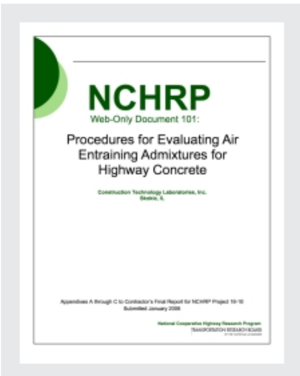

Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete

DETAILS

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SUMMARY OF LITERATURE

Introduction

Air entrainment is the process whereby many small air bubbles are incorporated into concrete and become part of the matrix that binds the aggregate together in the hardened concrete. These air bubbles are dispersed throughout the hardened cement paste but are not, by definition, part of the paste (Dolch, 1984). Air entrainment has been an accepted practice in concrete technology for more than 60 years. Historical references indicate that certain archaic and early 20th century concretes were inadvertently air entrained. The New York State Department of Public Works and the Universal Atlas Cement Company were among the first to recognize that controlled additions of certain naturally occurring organic substances derived from animal and wood byproducts could materially increase the resistance of concrete in roadways to attack brought on by repeated freeze-thaw cycles and the application of deicing agents (Whiting, 1983; ACI Committee 212, 1963; Rixom and Mailvaganam, 1986).

Highway structures in northern areas of the United States are exposed to severe winter conditions. Other areas of the country, normally associated with temperate or hot climates, may also be exposed to freezing and thawing. Frequently, concretes are exposed to freezing temperatures while saturated with moisture from rain or melting snow or ice. In addition, concrete pavements and bridge deck surfaces are exposed to large quantities of deicing agents. The process of freezing and thawing can cause deterioration of the concrete matrix. Although deicing salts are very helpful in maintaining traffic and improving safety, they can attack the concrete surface and lead to what is termed “scaling”. All of these processes can have severe consequences in terms of pavement rideability and structural integrity.

Concrete is susceptible to frost damage because it is porous. The pore structure of concrete consists of an interconnected pore system (capillary pores) representing the residual space occupied by mix water When subjected to freezing, concrete may be degraded due to the pressure generated by expansion of water on freezing or by the movement of super-cooled water from the gel pores to the capillary pores, where it can freeze. The mechanisms of frost damage are driven by the freezing of water in the capillary pores. However, the exact mechanism of frost damage is still not completely understood, even though it has been extensively studied for more than fifty years (ACI Committee 201, 1992; Powers, 1949). It has been established that concrete with a proper air-void system will sustain many cycles of freezing and thawing without serious damage. The entrained air voids provide empty space within the paste to which the excess water can move and freeze without damage, a form of “safety valve” to relieve the pressure.

Types of Air-Entraining Agents

Air-entraining admixtures (AEA) belong to a class of substances termed "surface-active agents" or surfactants. Surfactants, by definition are compounds that can lower the surface energy or surface tension of the air-water interface. Many chemical surfactants are used as air-entraining agents. Taylor (1990) describes air-entraining admixtures generically as long-chain molecules with a polar group at one end. They become concentrated at the air-liquid interface with their polar parts in the liquid and their non-polar parts in the air. Surfactants can be divided into three groups based on their polar portion of their molecules. If it is negatively charged, the surfactants are anionic. If the polar portion is positively charged, it is cationic and if it is electronically neutral, the surfactant is nonionic.

Until the early 1980s the majority of air-entraining agents were based solely on the salts of wood resin (neutralized "Vinsol" resin). This material is a by-product of a process for recovering various solvents and rosins from pine wood stumps. These were originally marketed as "Vinsol," short for "very insoluble," and later were trademarked as Vinsol resin. Because they are highly insoluble, they are neutralized with sodium hydroxide to form soluble sodium soap, which is the basis of commercial formulations (Whiting, 1983; Whiting and Nagi, 1998). Neutralization allows the admixture to form films around air bubbles immediately after addition to and subsequent agitation of the concrete mix, as it does not require any further reaction with alkalis generated by cement hydration. For this reason, entrained air is stabilized quickly with Vinsol resin air-entraining agents, and there is generally only a minor increase in air content with continued mixing, followed by air loss with prolonged mixing.

In addition to neutralized Vinsol resin (NVR), several groups of air-entraining admixtures are available but not widely used in highway construction. However, because of the limited supplies of Vinsol-based admixtures and their relatively high cost, other types of air-entraining admixtures are being used more frequently in highway construction in the last few years.

Air-entraining admixtures used in portland cement concrete have been classified into seven groups (Dolch, 1984):

- Group A- Salts of wood resins (anionic);
- Group B- Synthetic detergents (nonionic, anionic);
- Group C- Salts of sulfonated lignins (anionic);
- Group D- Salts of petroleum acids (anionic, nonionic, cationic);
- Group E- Salts of proteinaceous materials (anionic, cationic);
- Group F- Fatty and resinous acids and their salts (anionic);
- Group G- Organic salts of sulfonated hydrocarbons (anionic).

Anionic surfactants are the most widely used as air-entraining admixtures in portland cement concrete because of the stability that they grant to the entrained air voids. Admixtures based on cationic surfactants are rarely used in concrete because their cost is prohibitive and the stability that they provide to the air voids is questionable. Nonionic surfactants are not effective as air-entraining admixtures because the air-void system generated is unstable in concrete (Dodson).

As mentioned above, the hydrophobic compound in Vinsol resin is a very insoluble resin obtained from the stumps of pine trees. Over the past 15 years, the admixture industry has been employing other hydrophobic groups such as those obtained from the resins of plants other than pine trees, tall oils, and petroleum distillates. There is a loose distinction between those products with a “natural” source (i.e. plant oils) and those with a “synthetic” source (everything else). But given that all plant derivatives do not behave the same way, it is probably clearer to differentiate between Vinsol Resin (VR) and Non Vinsol Resin since VR has been the standard for so long. The issue is further complicated by the admixture manufacturer’s current practice of producing blends that carry the name of only one of the components (usually VR). Different sources of the hydrophobic compound means different molecular weights, different hydrocarbon chain lengths, and in the case of the natural sources, different mean chain lengths and range between the longest and shortest (Mielenz, Backstrom et al., 1958 a,b,c,d; Bruere, 1960, 1974; Powers, 1968; Bennet, 1977; Dolch, 1984; Rixom and Mailvaganam, 1986; Dodson, 1990). Cross et al. (2000) have conducted a variety of experiments addressing the fundamental behavior of air-entraining admixtures.

Mechanism of Air Entrainment

Air bubbles are not formed by air-entraining agents, but stabilized by them. The mechanical stirring and kneading actions of a concrete mixer generate the air in concrete. The shearing action of mixer blades continuously breaks up the air into a fine system of bubbles (Powers, 1965; Bruere, 1967). The smaller the bubble the more likely it is spherical in shape as surface tension effects predominate in small bubbles, while gravity effects predominate in larger ones. (Clift et.al., 1985)

Without the presence of an air-entraining agent, the bubbles incorporated in the concrete by the mixing are lost relatively easily, leading to rapid reduction of air content. The smaller bubbles, which have higher internal pressure, coalesce to form larger bubbles. The large bubbles have a greater tendency to escape as they come close to the surface and burst.

An air-entraining agent stabilizes the bubbles formed during mixing in several ways. First it lowers the surface tension. As the AEA molecules insert themselves between adjacent water molecules at the water surface, the mutual attraction between the separated water molecules is reduced. This is important because it is the surface tension of the bubble wall that exerts a confining pressure on the air trapped within, increasing bubble pressure over atmospheric pressure. Lowering the surface tension stabilizes the bubbles against mechanical deformation and rupture and also makes it easier for bubbles to be formed. Second, absorbed AEA molecules at the surface of the bubble form a film, with their polar heads in the water phase. If the molecule is charged the bubble acquires this charge. The electrostatic repulsion keeps bubbles separated and prevents coalescence (Dodson, 1990). Third, the ends of the air-entraining agent molecules that protrude into the water are attracted to cement grains. This allows for a coating of calcium salts (products of cement hydration) to form around each air bubble making it more stable than bubbles formed in plain water.

It should be mentioned that with an air-entraining agent, as with any detergent the temperature of the water will make a difference (Saucier et al., 1991). Some commercial detergents are formulated to work better in cold water, some in warm water, and some in all temperatures. Other complications include the shelf life of AEAs, particularly those made from natural sources. According to St. John (2002), bacteria growth can alter AEA behavior, and anti-bacterial additives can also make a difference.

While air-entraining agents provide the stability to air bubbles in concrete, gradual loss of air content with time is usually observed. The internal pressure, which is mainly due to surface tension, increases as the diameter of air bubble decreases. The tendency of air bubbles to slowly dissolve and saturate the mix water is very great as the diameter falls below 100 microns. It is rare to find bubbles in concrete less than 0.0004 in. (10 μm) in diameter, as the pressures within air bubbles so small are very great, forcing the air into solution and destroying the bubble.

Once the concrete is set, the entrained air bubbles are left behind in the hardened concrete as voids. Entrained air consists of microscopic voids ranging from 0.0004 in. (10 μm) to 0.04 in. (1 mm) in diameter which are uniformly distributed throughout the concrete. The air-void system of hardened concrete is evaluated using the microscopic technique specified in ASTM C 457, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete". In addition to the total air content, the specific surface and spacing factor are determined using this technique. The specific surface is defined as the ratio of internal surface area of the air voids to their volume. A larger calculated specific surface indicates a smaller average size of air bubbles. The spacing factor is the estimated maximum distance from any point in the cement paste to the periphery of the nearest air void. This value represents the average distance water would have to travel to enter an air void. A lower spacing factor indicates better freeze-thaw durability. In fact, the spacing factor is the most important factor controlling the freeze-thaw durability of concrete (Powers, 1954).

Effects of Air Entrainment on Properties of Concrete

Fresh Concrete

As mentioned in the introduction, the main purpose of air entrainment in concrete is to improve the freeze-thaw durability of the concrete. However, entrained air has significant effects on the properties of fresh and hardened concrete.

The adherence of the entrained air bubbles to the cement particles improves workability and decreases bleeding and settlement by increasing viscosity of the concrete. The small microscopic air bubbles act as “pneumatic cushions” which reduce inter-particle friction between cement and aggregate grains, thus improving workability of the mixture. Improvement of workability allows the reduction of water needed to achieve the needed slump. An increase in air content by ½ to 1 percentage point can increase the slump by about 1 inch. (Whiting and Nagi, 1998) On the other hand, the attraction between bubbles and cement particles imparts a cohesion or “stickiness” to the concrete that can make it more difficult to place, consolidate and finish, particularly at high air contents, and the compressibility of air can sometimes lead to problems in pumping.

Hardened Concrete

The main hardened concrete propertied affected by air entrainment are compressive and flexural strength and modulus of elasticity.

The strength loss is usually manifested when the 28-day compressive strength is found to be less than the design strength. An increase in air content by a percentage point leads to an average reduction of 3 to 5% in compressive strength. However, strength reductions have recently been noted in concretes having normal air contents. Strength reductions of 20% or more have been observed in concrete pavements. In some cases, when Vinsol resin was replaced by non-Vinsol admixtures, the 28-day compressive strengths dropped even for comparable air contents. It was reported that there was more than the usual debonding of aggregate particles during compression testing. A failure mode of mostly shear at the interface between aggregate and paste was noticed, with very few fractured aggregate particles. Microscopic examination indicated accumulations of air voids around the aggregate particles. Figure 1 shows a typical example. The presence of excessive voids around the aggregate reduces the bond strength between the aggregate and surrounding mortar, leading to this type of failure.

The coalescence of air voids around aggregate particles and its effect on strength is not a new phenomenon. However, very few cases were reported in the past. Hover (1989) reported a case study in which the accumulation of air bubbles at the mortar/coarse aggregate interface led to debonding of aggregate particles and reduction in strength. The South Dakota DOT conducted a comprehensive investigation to define the causes of compressive strength reduction observed during the construction season of 1997 (Cross et al., 2000). The report concluded that incompatibility between low-alkali cement and synthetic admixtures caused the coalescence of air-voids around the aggregate particles and that high summertime temperatures aggravated the problem. The thinner-walled air bubbles formed by these admixtures apparently caused more flocculation than would be observed with Vinsol resin admixtures.

It should be mentioned that there is less decrease in flexural strength than for compressive strength for each percentage of entrained air added. The flexural strength decreases from 2 to 4 percent for each percent of air content.

The effect of air content on elastic modulus (in compression) is similar to that on compressive strength. The elastic modulus will usually decrease from 2.5 to 6 percent for each percent of air added to concrete (Whiting and Nagi, 1998).

Factors Affecting Air Entrainment

In addition to air-entraining agents, all materials used in concrete (portland cement, supplementary cementing materials, water, chemical admixtures, sand and aggregate) influence, to a certain degree, the air-void system (Whiting and Nagi, 1998). Production procedures, construction practices and field conditions will also affect the air-void system of concrete. The effects of these factors on the air-void system have been studied extensively. Recently the focus of research has been on specific issues such as the effect of chemical admixtures and their compatibility with air-entraining admixtures and supplementary cementing materials.

Effect of Concrete Materials

Portland Cement

The cement is the primary source for the calcium ions that adsorb to the bubble wall, and the surface charge on the cement grains provides opportunity for anchoring the bubbles against buoyant rise. Cement also increases the effective viscosity of the paste, inhibiting bubble loss. It also seems likely that the paste increases the effective surface tension of the bubble wall, inhibiting expansion of the bubbles (Hover, 1988). Since the cement grains are charged (as measured by their zeta potential), they can also attract the hydrophilic ends of the AEA molecules even before the formation of bubbles. One might expect that the more cement, the finer the cement, and the stronger the charge the more of the AEA will be taken up by attraction to cement and the less available for forming bubbles. This is what is observed, as AEA dosage must increase with cement content and fineness to maintain a constant air content (Klieger 1994; Whiting and Stark, 1983; Nagi and Whiting, 1994). Scripture and Litwinowicz (1949) collected a data set on the variability of air content, in which a matrix of 12 cements by three AEAs with a non air-entrained control were batched with identical proportions. The resulting air contents ranged from 1.0 to 3.1% for the non-air-entrained mixes, and 2.0 to 8.1% for the air-entrained mixes.

The alkali content of the cement has been shown to be important and controversial. Alkali contents (expressed as equivalent Na_2O) range from 0.2 to over 1%. It is the water-soluble alkali that affects air entrainment. For a given dosage of AEA, the air content increases with the alkali content of the cement. Alkalis allow more air-entraining agent to remain in solution during mixing, maintaining lower surface tension longer and leading to greater volume of air entrained. This phenomenon is related to the concentration of calcium ions in solution. Air-entraining agent is precipitated by calcium salts. An increased alkali concentration in solution reduces the concentration of calcium ions.

There is a question, however, about the stability of air bubble systems formed in a high alkali environment. Nagi and Whiting (1994) observed “higher discrepancies” between fresh and hardened air contents with high alkali cements, as has been reported by others. Pigeon et al, (1992) not only found “no differences in air-void stability” between 0.4 and 0.6% soluble alkali, but also found that a higher alkali content can increase the stability when superplasticizers are present. They also acknowledged that for different mixes and dosages, other researchers found contradictory results (Greening,1967; Whiting and Stark, 1983; Pistilli, 1983).

St. John (2002) has pointed out that a frequently overlooked factor is the cement grinding aid. It was the discovery that cements that incorporated a grinding aid produced a more scale-resistant concrete that led to the development of air-entrained concrete in the first place (Mattimore, 1936, Swayze, 1941; Gonnerman, 1954; Hansen, 1961; Klieger, 1994). The oils, tallows, and resins that were added to improve grinding efficiency remained in the cement and in effect unintentionally produced air-entraining cement. Although the grinding aids in use today may differ somewhat from those of 60 years ago, they are nevertheless surfactants and are used in dosages that are comparable to that of air entraining admixtures (Taylor, 1997). The presence of grinding aids can also explain why non air-entrained concrete can have considerable air content and can in some cases be freeze-thaw durable. When residual grinding aid is present one may expect that the dose of AEA will be reduced to achieve a given air content, and if the residual grinding aid in a given shipment of cement decreases from the norm, air content will drop until the problem is corrected and the AEA dose increased. The tendency for the cement to entrain air can be determined by the ASTM C 185 Test for Air Content of Hydraulic Cement Mortar. Both the air content achieved and variability between successive tests are of interest (Struble and Hawkins, 1994).

Given that the job of the AEA is to stabilize the bubbles long enough for the concrete to set, setting time is indirectly a factor that can influence the final air void system. The longer the setting time, there is more opportunity for changes in the bubbles. This also means that accelerators and retarders can have an effect as well, as will any other admixtures that affect setting time such as silica fume and corrosion inhibitors that act as accelerators, and fly ash, slag, and superplasticizers that act like retarders.

Supplementary Cementitious Materials

Fly ash, ground granulated blast furnace slag, silica fume, and natural pozzolans interact with air entraining admixtures and air bubbles similarly to the way that cement does, with some notable exceptions. These exceptions have been the source of controversy.

Fly Ash

Fly ash has been used successfully in concrete for decades. Fly ashes are the finely divided residue resulting from the combustion of ground or powdered coal. Its pozzolanic nature causes it to react with calcium hydroxide in the presence of water to form calcium silicate hydrate. With the abundance of water and free calcium hydroxide in the pore solution of concrete a pozzolan will beneficially react with these components to replace the void space in concrete with solid material. This not only increases compressive strength, but also lowers the concrete's permeability and reduces the potential ingress of aggressive chemicals into the concrete matrix. Two major classes of fly ash are specified in AASHTO M 295 on the basis of their chemical composition resulting from the type of coal burned; these are designated Class F and Class C. Some of the benefits of using fly ash in concrete include increased workability and pumpability, decreased bleeding, improved sulfate resistance, mitigation of alkali-silica reaction (ASR) and control of thermal cracking in massive concrete elements such as bridge foundations or piers.

The major challenge associated with using fly ash in highway structures is ensuring that an adequate air-void system is developed in the concrete. The adverse affects of fly ash on the ability to produce a suitable air-void system in concrete are well documented (Mather, 1954; Pasko, 1962). Generally, a higher dosage of air entraining admixture is needed in concrete containing fly ash as compared with a control (Klieger, 1983; Isenberger, 1981). Fly ash is usually finer than cement. Therefore, when fly ash is used to replace a percentage of cement in a mixture, a higher dosage of admixture will be required to account for the increased surface area of cementitious material. It has been known for quite some time that the carbon content in fly ash is responsible for adverse affects on air content. Some researchers suggest that the carbon found in fly ash is similar to activated carbon, which would have the ability to attract and adsorb surfactants used in air entraining agents (Klieger, 1976; Ramachandran, 1984).

The chemistry of fly ash produced by different power plants is highly variable and often varies within the day-to-day operation of a single plant. In order to avoid the ill effects of carbon, state transportation departments and specification agencies have adopted the practice of limiting the loss on ignition (LOI) percentage of fly ash that is to be used in concrete. Loss on ignition is a measure of the unburned carbon or organic constituents in fly ash. However, some fly ashes with a high LOI do not necessarily contain significant amounts of reactive carbon. This is possibly due to carbon phases that become encapsulated in glass spheres during cooling and are prevented from absorbing the surfactants or when a portion of the LOI is due to carbonate (Detwiler 1996).

While most standards limit carbon contents to five percent or less, some researchers have found fly ashes with LOIs in the range of 3 to 4% that are very problematic (Hill, 1997). These researchers suggest that it is not the amount of carbon, but rather the chemistry and surface area that dictate its absorptive capacity. They point out that fly ashes with similar LOIs can have carbons with significantly different surface areas. In addition, Klieger (1983) and Kleiger (1983) have also suggested that organic components other than carbon in fly ash may interact with air-entraining agents and reduce their effectiveness. Therefore all fly ashes should be tested before accepting or rejecting a specific source for a job.

Another chemical component of fly ash that receives considerable attention is the calcium oxide or lime content (CaO). The lime contents of Class C fly ashes are generally much higher than Class F fly ashes; however, it is possible for some Class F ashes to possess lime contents on the order of 15% by mass. With respect to air-void stability, Rodway (1988) studied the effect of five different fly ashes with lime contents varying from 0.7 to 24.3% CaO. He concluded that the air-void system was satisfactory regardless of lime content.

Gebler and Kleiger (1983) performed extensive research on the effect of fly ash on the air-void stability of concrete. Their study included 10 fly ashes with variable chemistries. The main focus of the study was air-void stability over time by casting specimens 30, 60, and 90 minutes after initial mixing. In general they found that the spacing factors, specific surface, and voids per inch for both Class F and Class C fly ashes were similar for placing times up to 60 minutes. However after 90 minutes, differences began to appear. As the dosage of admixture required increased, air loss in the plastic concrete increased. In general, concrete containing Class C ash tended to lose less air than concrete containing Class F fly ash.

One area of interaction that has not been studied in detail is the effect of particle charge. When fly ash, for example, is used as a partial cement replacement, one might expect the impact on air to be neutral if the particle size of the ash is similar to that of the cement, and if the total alkali content is about the same, and if the surface charge of the fly ash is about the same as that of the cement. If the ash has a neutral charge then the air bubbles will be destabilized as a portion of the “cementitious anchors” will not be available. If the surface charge of the fly ash is opposite to that of the bubbles then stability is favored. If the surface charge of the ash is the same as that of the bubbles, instability is favored. Fly ash is collected at the power plant by means of electrostatic precipitators that induce a 60,000 volt electrical field across the exhaust air stream. The particles become charged and are attracted to the collector plates. The residual charge and possible subsequent effects on air bubbles is not known. See Rachel’s note

<u>Blast Furnace Slag</u>

Ground granulated blast furnace slag (GGBFS) is the glassy byproduct of iron in blast furnaces. It is formed when molten iron blast furnace slag is rapidly chilled by immersion in water (quenching). In contrast to most applications of fly ash, GGBFS is normally used at high dosages, generally up to 50 percent by mass of cementitious materials (more in mass concrete).

Dosage of AEA in concrete containing GGBFS will be a function of the fineness and amount of GGBFS used. GGBFS is usually finer than cement; therefore, a higher dosage of AEA may be required to achieve the target air content. In some cases, up to 100 percent more AEA may be needed for finely ground GGBSF used at higher dosages. It should be mentioned that GGBSF, unlike fly ash, does not contain carbon, which may lead to air loss in concrete.

<u>Silica Fume</u>

Silica fume is a byproduct of the reduction of high-purity quartz with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys. In contrast to fly ash and GGBFS, silica fume is normally used at dosages between 5 and 10 percent by mass of cement (in ternary mixes it would be more like 3 to 6%).

It has been found that silica fume does not have a significant influence on the production and stability of the air-void system, but due to its fineness higher amounts of air-entraining agent are needed (Whiting et al.1992)

Chemical Admixtures

Certain combinations of water reducers and air-entraining admixtures can be incompatible, in such a way as to lead to unacceptable air-void systems. Plante et al. (1989) indicated that increasing the dosage of water reducers influences the air-void system. Doubling the recommended dosage of any of three water reducers in their study negatively influenced the stability of the air-void system. However, there was no consistent relationship between the admixture dosage and the resulting air content.

Accelerating admixtures have a minor effect on the air-void system. Stott et al. (1994) studied the effect of both calcium chloride and non-chloride accelerating admixtures on frost durability. They found that the air content and spacing factor of mixes containing accelerating admixtures did not differ from those of the control mixes.

In their study on the effect of superplasticizer on freeze-thaw durability, Attiogbe et al. (1992) indicated that properly air-entrained concrete containing superplasticizer could have adequate frost resistance even if the spacing factors were relatively high. Spacing factors exceeding the ACI recommended maximum values of 0.008 in. (0.20 mm) were determined in their concretes, yet the frost resistance was acceptable.

Aggregate

Aggregate maximum particle size, gradation, fine-to-coarse aggregate ratio and surface texture influence to a certain degree the entrainment of air in concrete.

Air content of concrete decreases as the aggregate size increases. This is due to the fact that using larger aggregate reduces the mortar fraction in a unit volume of concrete. Since the entrained air is contained within the mortar fraction, it follows that the air content expressed as a volume percentage of concrete will decrease in proportion to the decrease in mortar (Klieger, 1956). It was found that there is little further change in air content for maximum aggregate size over 1.5 in. (Whiting and Nagi, 1998).

In a field study of six pavement sections in Missouri, the influence of aggregate maximum size on the air-void system was studied (Missouri DOT, 1987). The aggregate maximum sizes ranged from ½ to 1.5 in. It was found that aggregate size and the fineness modulus of the combined fine and coarse aggregate affected the spacing factor. The spacing factor increased as fineness modulus decreased. The study indicated that the specified air content should be increased in order to reduce the spacing factor below the recommended values (0.008-in. (0.20 mm)).

Sand contributes to air entrainment by trapping air bubbles in the void spaces between sand grains. This mechanism is known as "aggregate screen effect." In very fine sand, less than 100 mesh, this effect diminishes as the effective screen size approaches the size of the largest bubbles.

Air content increases with increasing sand content; therefore, the dosage of air-entraining agent needs to be decreased as the sand content is increased in order to maintain the same air content (Taylor, 1949).

The grading of sand can influence air content. Sand in the middle size fractions of No. 30 to 100 is most effective in entraining air. Increasing the proportion of sand in this size range will result in an increase in the air content of concrete. It should be mentioned, however, that the effect of sand grading is significant only in sand-rich mortars. In normal concrete, where the sand is less than 50% of total aggregate volume, the effect is usually not of great importance (Johansen, 1967).

As mentioned above, other properties such as surface texturing and condition of aggregates. Crushed stone aggregate will entrain less air than gravel aggregate (Dodson, 1990). Buenfeld, (1999) showed that saturation of the aggregates influences the air-void system in concrete. When partially saturated aggregate was used in concrete, air bubbles, typically 100 microns in diameter, were formed at the surface of coarse aggregates leading to noticeable strength reduction. The researchers claimed that air, trapped under pressure inside aggregate particles during water absorption, migrated out between concrete placing and setting to produce the voids.

Effects of Production Procedures

The issue of air bubble stability starts at the mixing phase, as the air content and other characteristics of the air bubble system vary with time during mixing. As shown in Figures 1 and 2, air content is not constant with time even before the concrete is discharged, placed, consolidated, and finished.

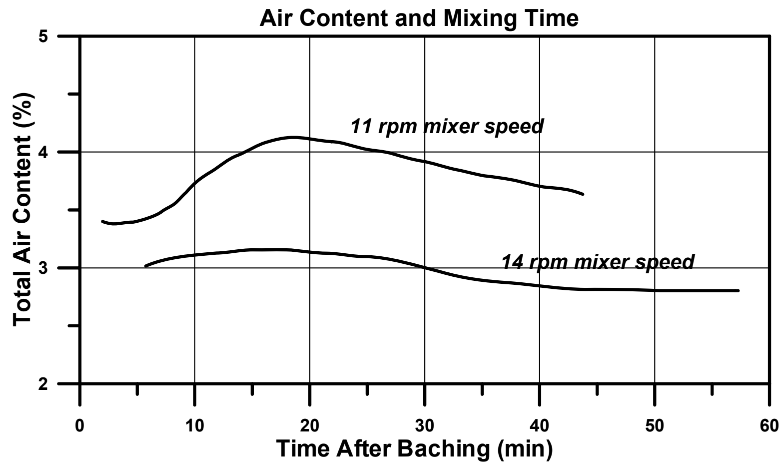

Figure 1. Variability of air content as a function of mixing.

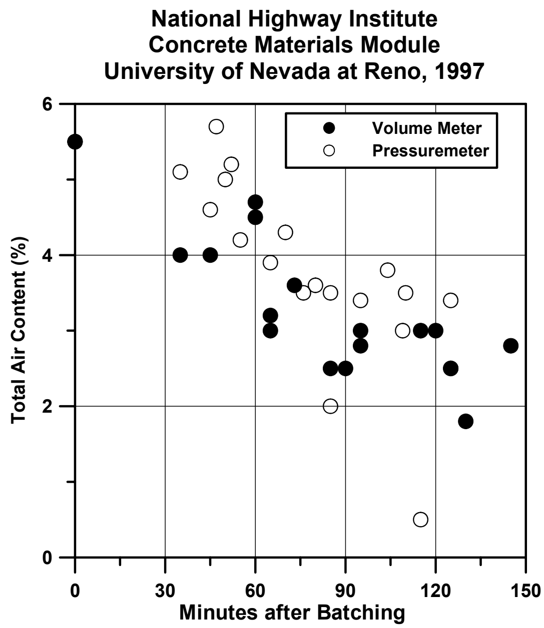

Figure 2. Thirty-five air tests on one truckload of concrete, sampled from the truck chute.

Figure 1 shows typical behavior for a Vinsol Resin air-entraining admixture. Some non-VR admixtures may behave differently, with some products continuing to develop higher total air content for a comparatively longer period of time.

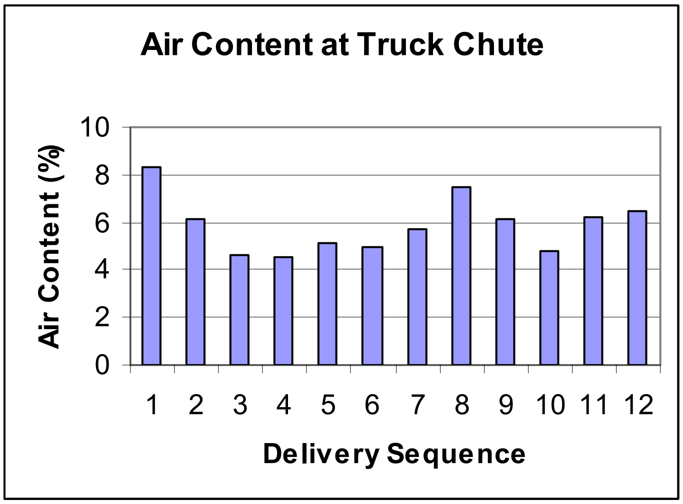

Figure 3. Variability of air content at the truck chute prior to placing. Such variability makes it difficult to diagnose the impact of construction operations on air content. (Hover and Phares, 1996)

The net result is that the concrete delivered to the construction site can have a highly variable air content (and variable air bubble characteristics) before any modifications induced by handling, placing, consolidating, or finishing the concrete. In the full-scale pumping tests conducted by Schwing America, the air content of concrete as delivered to the construction site and as measured upon discharge from the concrete truck chute varied as shown in Figure 3.

Type of mixer, mixing speed, and mixing time have a significant effect on air content generated in fresh concrete. It is known that certain types of mixers, such as high-speed turbine central mixers, are more efficient on low-slump concretes than other types, such as ready mix trucks, which may be more appropriate for concrete with higher slumps (Gaynor, 1974).

For a given mixer, the mixing time plays an important role in controlling the concrete air content. The air-void system develops during mixing. An adequate air-void system can be achieved in as little as 60 seconds of mixing (Barbee, 1961). Variations in air content are much higher for a concrete produced at extremely short mixing times. A batch-to batch variation of 40% was reported for concrete mixed for 15 seconds compared to a 4% variation for a concrete mixed for 120 seconds.

Recently, the German Cement Works Association (VDZ) conducted a research project concerning the effects of mixing time and admixture type on air-content (Eickschen, 2002). The project, sponsored by the German Traffic Ministry, was awarded to VDZ because of recent problems associated with unwanted increases in concrete air-contents. Various German companies began reporting instances where concrete left the mixing plant with normal air-contents of 4 to 5%, but later found that the hardened air content in core samples was 10% or more. Furthermore, this behavior was found to occur especially in the summer months and with the use of synthetic (non Vinsol) admixtures.

The research project involved six different air-entraining admixtures (three Vinsol resin and three synthetic admixtures). Air-contents were measured after mixing times of 0.5, 1, 2, 4, 6, 8, 10, and in some instances up to 15 minutes. When using standard dosage rates of AEA, the air-contents remained relatively constant for mixing times up to 10 minutes. However, when the standard dosage was doubled, normal air-contents were observed for short mixing times of up to one minute, but continued mixing produced dramatic increases in air-content. The German Cement Works Association hypothesized that many of the air-entrainment problems could have been related to increased dosages of admixture that were not fully activated during short mixing times at the plant, but appeared later on when additional energy was used to place the concrete.

Construction Practices and Field Conditions

Construction practices such as retempering (adding water to restore consistency), temperature, prolonged vibration (or over-vibration), and pumping, may lead to alterations in the air-void system of concrete. Compared with other construction factors, placement temperature can be more critical and more difficult to control. If considerable air is lost due to any of the above factors, there may be insufficient air bubbles left to achieve the necessary spacing factors, which are required to ensure good freeze-thaw durability.

Retempering

Adding water to concrete and subsequent mixing will increase the air content. The amount of added water and the resulting effect on air content will depend on the slump, air content, and concrete temperature prior to retempering. For a concrete with 6% air content, retempering can be effective in maintaining air content for up to 4 hours after initial mixing.

Nagi and Whiting (1994) evaluated the effect of retempering on the air-void system. To simulate retempering, the concrete was left in the mixer for a total two to three hours after initial mixing and remixed for one minute every ten minutes until the slump decreased to 1 in. Water was then added to the mix to bring the slump back to the initial value of 3 to 5 in. The studied showed that retempering at normal temperature did not influence the air-void parameters (e.g., spacing factor). The change in air content varied: for some AEA's the air decreased by more than 2 percentage points, and for others the air increased by an average of 2 percentage points.

Temperature

Higher temperatures necessitate higher dosages of air-entraining admixtures in order to maintain a given air content (Whiting and Nagi, 1998). Powers (1965) indicated that temperature rise would lead to relatively rapid hydration of cement. Therefore, less water will be available for bubbles to be formed. Saucier et al. (1991) found that, while changes in temperature lead to changes in the total air content, the spacing factor of the hardened concrete is not significantly affected. The effect of temperature on air content of concretes with different slumps is shown in Figure 4. As mentioned earlier, it has been observed recently that at high placement temperatures some new air-entraining admixtures can cause the air bubbles to accumulate at the surfaces of aggregate particles, weakening the concrete (Cross, 2000).

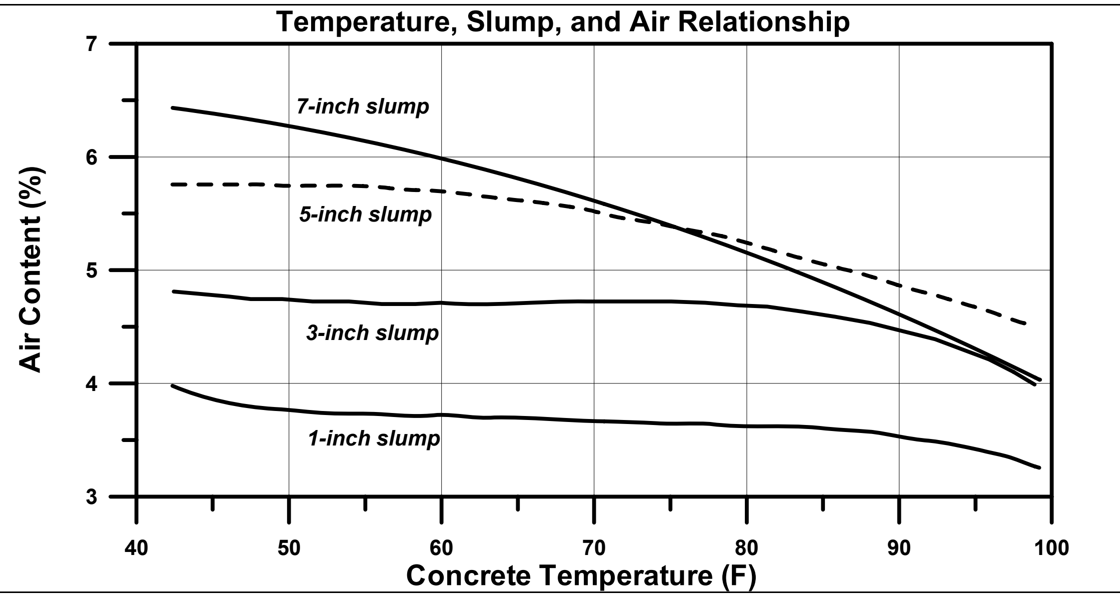

Figure 4. Variability of air content with slump and temperature.

Consolidation

Consolidation is normally carried out by vibration, which reduces the friction between the aggregate particles and makes the concrete more flowable and easier to consolidate (Whiting and Nagi, 1998). For slip-form paving, internal vibrators are usually spaced at a maximum of 18 to 24 in. and operate at frequencies from 5000 to 10,000 vibrations per minutes (vpm). The purpose of vibration is to remove pockets of entrapped air in fresh concrete. However, vibration can also cause a loss of entrained air from fresh concrete, especially if the vibrator is held in place for too long. The loss of air content due to vibration depends on the concrete slump, initial air content, vibration frequency and time of vibration. Studies have shown that for a given vibration frequency and vibration time, the loss of air increases with slump (Higginson, 1952). An increase in vibration frequency also has a significant effect on the air-void system. The spacing factor significantly increases for concrete subjected to 20 seconds of vibration at frequencies of 11,000 and 14,000 vpm (Stark, 1986). However, for frequencies of 8000 vpm or less, even though the air content is decreased the spacing factor remains relatively unchanged.

In some concrete pavement construction, scaling due to cycles of freezing and thawing is observed in paths following the vibrator heads on the paving machine. This is due to excessive vibration (Stark, 1986). The Iowa DOT has observed an increase in premature deterioration in concrete pavements related to over vibration. This problem has been noticed on several portland cement concrete pavement projects across the state. Tymkowicz and Steffes (1999) reported that cores taken from longitudinal cracks in Interstate 80 in Iowa contained 3% air in the top half and 6% in the bottom half. They attributed this behavior to excessive vibration. They stated that excessive vibration occur at lower paver speeds even though the frequency was (8000 vpm). Therefore, for vibration frequencies of 5000 to 8000 vpm, they recommended that the paver speed should be greater than 3 ft. per minute. Their investigation indicated that the radius of effective consolidation of the vibrator was smaller than previously believed. Cores taken between vibrator trails showed significant entrapped air within 4 in. of the vibrator location. Stutzman (1999) conducted a similar study on Iowa pavements and found that the air-void systems of deteriorated pavements were worst in the visible vibrator trails.

Pumping of Concrete

Pumping is the most critical placement technique influencing concrete air content and the air-void system. Pumping affects air entrainment by two mechanisms, namely free-fall and pumping pressure.

Freefall Mechanism

Air bubbles are fragile, gas-filled, buoyant, tension structures suspended in the mix water and competing for space with cement and aggregate particles. These elastic bodies are susceptible to buoyant rise and loss, collapse, breakage, or puncture due to shock, impact, sudden compression or decompression, or vibration. When handling concrete the material is often dropped, with an accompanying loss in air content. Gorsha (1992) pointed out that "Air entrained concrete dropped into place in any manner - crane bucket, tremie, pump hose, or truck chute with more than a 5 foot free fall could be subjected to a dramatic reduction in entrained air." Hoppe (1992) made similar observations. Yingling et al. (1992) demonstrated the same principle, as did Hover and Phares (1996). Several researchers have been able to trace part or all of the observed loss of air associated with pumping to the impact of concrete as it falls freely down an unfilled pipeline, hitting pipe elbows and eventually splattering at the point of placement. This low frequency but variable intensity pulsing of the concrete is normally associated with the loss of coarser air bubbles and what can be a significant loss of total air content. Since large voids make only a small contribution to freeze-thaw protection, such losses are often inconsequential in terms of the in-place durability of the concrete (Hover, 1989; Pleau et al., 1995; Lessard et al.; 1996; Hover and Phares,1996; Pleau et al., 1998).

In full-scale field tests Hover and Phares (1996) demonstrated that air lost from a Minnesota DOT concrete mix during pumping was predominantly from the larger bubbles, resulting in a finer residual air-void system. The air-entraining admixture was a 50/50 blend of fatty and resin acids, and the maximum pumping height was 73 feet. In freeze-thaw tests concrete that lost 2% or more air was still durable. Since the air-void system was made finer, it is likely that the principle mechanism of air loss was the bursting of larger voids upon free fall or upon exit from the pipeline. This was verified by similar losses and a refinement of the air-void system when the same concrete mixture was dropped from either a concrete bucket or from a conveyor. When steps were taken to reduce free-fall and impact, air loss was reduced. Similar results were demonstrated by Yingling et al. (1992), and by Pleau et al. (1995).

Pumping Pressure

Pumping can change the air bubble system in fresh concrete by free fall and impact as already described, and by compressing and subsequently de-compressing the air bubbles. At sufficiently high pressure the pump can compress the bubbles to the point of dissolution of the air into the mix water. The pressure required to do this and the time it would take for air to escape the bubble wall depend on the initial bubble size, and the surface tension and permeability of the bubble wall. As postulated by Meilenz (1958 a,b,c,d) and summarized by Fagerlund (1990), smaller bubbles and lower surface tension will favor air dissolution. When the concrete is depressurized the air comes out of solution at a rate that is determined by the rate of depressurization. Slow, reversible depressurization allows bubbles to reform into approximately their initial state. Rapid, uncontrolled depressurization allows the air to explosively come out of solution, escaping from the mixture or perhaps forming into large bubbles, immediately susceptible to loss on impact. Multiple researchers have demonstrated the benefits of controlled depressurization in reducing air loss by means of various attachments and hose configurations (Yingling et al., 1992; Macha, Zollinger, and Szecy, 1994; Pleau et al., 1995; Lessard et al., 1996; Hover and Phares, 1996).

Several studies have concentrated on the effects of the peak pressure experienced by the concrete during pumping. Pleau et al. (1998) observed only 1 to 1-1/2 percent air lost in pumping, but the air-void system was significantly coarsened to the point of putting the freeze-thaw durability in question. The same coarsening was observed in both field and laboratory tests, and the authors developed a simple and reliable linear equation relating the increase in spacing factor to the pump pressure. In these tests a synthetic air-entraining admixture and a naphthalene-based superplasticizer were used, with the superplasticized mix evidently less stable when pumped. Pressures were reported from 0 to 3 MPa above atmospheric pressure, and air bubble coarsening was observed at all pressures above atmospheric.

In contrast to Pleau's consistently linear effect of pressure for all mixes, Elkey et al. (1998) observed substantially no coarsening of the air-void system until the pressure hit a threshold value that depended upon the mixture. This threshold was between 1 and 2 MPa for Elkey's spectrum of mixes. For example, VR admixtures were generally more stable than tall oils, and the combination of a synthetic detergent /tall oil AEA with a lignosulfonate WRA and a Class F fly ash proved to be highly stable at pressures up to 2 MPa. Once the pressure exceeded the threshold for a particular mix, Elkey observed the coarsening of voids and increase in spacing factor as in Pleau's tests. On the other hand, Macha and Zollinger (1994) also conducted full-scale pumping tests and observed a refinement of bubble sizes with *Daravair* and Concentrate AES air entraining admixtures, and a coarsening of bubble sizes with *Sika AER* and Relcrete Air 30. Zollinger's pressures (in the range of 0.2 to 0.3 MPa) were considerably lower than Elkey's and Pleau's but nevertheless realistic, and about the same as the pressures in Browne's much earlier tests to determine pumpability of concrete mixtures. (Browne and Bamforth, 1977).

From these tests and from reports from the field it is clear that pressure is an important factor in air-bubble stability, but pumping pressures can vary so widely that any given mixture may perform acceptably or unacceptably depending on site conditions. Differences in the pumping pressures, which can vary from less than 1 to more than 10 MPa (Browne and Bamforth, 1977; Cooke, 1990; Eckardstein, 1983; Janssen et al., 1991), explain the conflicting reports from the field and the laboratory concerning the influence of pumping on air-entrained concrete.

Zollinger's group (Macha, 1994) generally concluded that lowering the pumping pressure could reduce air loss. They reasoned that any factor that reduced the pressure required to pump the concrete would indirectly contribute to air-bubble stability, and thus observed that improving the combined aggregate grading by inclusion of an intermediate aggregate was effective in this regard. They also observed a trend of increased air stability for AEAs with higher surface tension. Higher surface tension at the air-water interface increases the internal pressure in the bubbles, which generally discourages the formation of smaller bubbles. As early as 1958 Meilenz et al. (1958 a,b,c,d) postulated the benefits of lowering the surface tension to stabilize finer air-void systems, and Hover (1988) investigated these effects analytically. As seen earlier, Fagerlund (1990) postulated the air-loss mechanisms of diffusion of air from air bubbles, and the transfer of air from smaller to larger bubbles, and both effects would be more pronounced when the concrete is pressurized (as in pumping) and more pronounced for systems of smaller air bubbles. Fagerlund's hypothesis thus supports Macha, Zollinger, and Szecsy's observations about surface tension and bubble stability. Yang et al., (2000) have developed a Saponin-based AEA that favors the formation of smaller voids by virtue of a lower surface tension (as the major international admixture companies have done for some time). This new product appears to be more stable in the presence of superplasticizers, is stable in hard water, and evidently avoids the strength loss problem at higher air contents. However, based on the Texas studies, this product might be expected to be less stable in high-pressure pumping.

Surface Finishing

Air loss due to finishing may be seen as a special case of the mechanisms already discussed, but concentrated at the surface and near-surface of the concrete. Use of a vibratory screed, for example, is merely surface-applied vibration, which would result in the types of effects already discussed. Most vibrating screeds have a lower frequency than insertion vibrators, however, so normally only the coarser voids would be influenced. Later finishing operations are not only higher frequency but also are more concentrated at the surface as the concrete hardens. The bursting of air bubbles can be observed at the trailing edge of finishing tools as they are passed over fresh concrete, and there is clearly a surface impact as the blades of a float- or trowelling-machine strike the concrete surface. It is also possible that machine finishing results in a localized frictional heating of the surface that may contribute to air loss. Rodway (1979) was among the first to document the loss of freeze-thaw durability at the finished surface compared to fully satisfactory durability at depth. Meyer (1998) reported that machine finishing was discontinued on the Great Belt Link West Bridge project in Denmark due to degradation of the air-void system and loss in surface durability. Contributing to this type of problem is not only the loss of air, but also the incorporation of bleed water into a thin surface layer, with a dramatic localized increase in water content, w/c, porosity, and permeability, and a localized decrease in strength. This means that finishing operations have to be properly timed with the overall sequence of bleeding and setting. Of course any effects of surface finishing will be closely related to the effects of curing, which are beyond our current scope.

SUMMARY OF FIELD PERFORMANCE

Materials divisions from all 50 states were contacted. Interviews with State DOT personnel focused on their experience with air entrainment in concrete including the use of the new generation of air-entraining admixtures and their effect on air-void systems in highway structures. Testing of air-entraining admixtures and research being conducted in the area of concrete air-entrainment were also discussed.

Performance of air-entrained concrete varies regionally, based in part on available materials, climate, and specification requirements. All persons interviewed reported periodic problems. In fact consider some consider the incidence of low or high air contents, inadequate air-void systems, questionable testing, and potential admixture interactions to be “business as usual for air-entrained concrete.”

Everyone interviewed was aware of problems with incompatibility between admixtures and other ingredients (especially with the so-called “synthetic” air-entraining admixtures). Everyone was also familiar with the phenomena of clustering of air-voids near the aggregate interface, although few have actually experienced the problem. New Jersey and South Dakota have aggressively studied the problem. South Dakota’s comprehensive report was published in 2000. A summary of their report was presented in the literature review section of this Chapter.

The issues of terminology, “synthetic admixtures”, and the availability of Vinsol resin were also discussed. In some cases, the term “synthetic air-entraining admixture” is used to refer to any product not containing Vinsol resin. As such, the common tall oil admixtures based on natural wood derivatives are classed by some as “synthetics.” In other cases the term “synthetic” is used to refer to only those products that can be synthesized in the laboratory, without dependence on a naturally occurring source. It appears that the Vinsol resins are readily available now, but it is quite certain that their continued availability in the future will be limited.

The most severe problems have been reported in the northern states where the requirements for frost protection are more stringent and where routine testing evaluated both air content and concrete strength. Wisconsin, Minnesota, South Dakota, and Iowa have reported serious problems and have taken a number of actions to overcome them.

The state of Wisconsin associates an increase in the incidence of air problems with a decrease in the availability of Vinsol resin admixtures. They have also observed higher air contents in the hardened concrete than would have been expected from tests on fresh concrete. The difficulty in fully documenting problems when they occur makes it difficult to diagnose after the fact.

For the last 10 years, the state of Iowa has been dealing with the issue of air-related durability problems that have been addressed with a combination of changes to both materials and construction specifications. Iowa had previously observed “vibrator trails” in slip-formed pavement, and instituted maximum and minimum limits on vibrator frequency to ensure consolidation and to limit damage to the air void system. A summary of their finding is presented in the literature review section of this report. Occasional problems still occur such as air loss in handling and the compatibility of ingredients with different cements, ashes, GGBFS, and admixtures

In Minnesota, MinnDOT has had a similar experience to that of Iowa. They have benefited by improving their mixture designs, which incorporated combined aggregate grading. This has made it easier to place the concrete, and MinnDOT has noted a decrease in air-entraining problems as well

Some states took preventive measures to overcome problems associated with air entrainment. The Kansas DOT, for examples modified mix compositions to overcome the instability of the air-void system. They found that the use of water reducer helps in improving the air-void system. Also, they introduced the Air-Void Analyzer method to measure air-void parameters in fresh concrete. The state of Iowa’s mandated approach to combined aggregate grading has in general lead to more workable concrete, requiring lower water contents and lower frequency vibration. Iowa routinely tests concrete ahead of and behind the paver during the construction of concrete pavements. The improved combined grading has also improved the stability of the air bubbles, as there are less overall problems with air using better aggregate combinations. They observed more difficulties in achieving a reliable, stable air-void system in hot weather and with short mixing times. Occasional problems still occur: air loss in handling, compatibility of ingredients with different cement, ashes, GGBFS, and admixtures. The state personnel suggested that acceptable air contents but unfavorable air-void systems are developed more commonly problem with central mixed concrete. They suspect that with some combinations of materials the time in the central mixer is insufficient to build a good air-void system. Most agree that air problems are, generally exacerbated in hot weather.

One of the issues mentioned by several states involves controlling air content in concrete that is being pumped in bridge construction. Changes in the air content of fresh concrete during pumping can influence the durability and strength of the concrete.

The state of New Mexico indicated recent problems associated with air-entrainment. Petrographic examination of cores taken from a newly constructed bridge showed significant air-void clustering around aggregate particles.

Measurement of air content was also brought up during the interviews with state DOT materials. They suggested that the inability of the pressure meter to measure very small entrained air bubbles may lead to discrepancies in measured air content between fresh and hardened concrete.

It seems that more state DOTs are concerned about measuring air-void parameters other than total air content.

SURVEY OF AIR-ENTRAINING ADMIXTURES USED BY HIGHWAY AGENCIES

A survey was conducted to identify the air-entraining admixtures used by highway agencies in the U.S. Lists of approved admixtures were obtained from materials laboratories of the state DOTs. All admixture manufacturers in the U.S. were contacted. A general catalog of air-entraining admixtures available in the U.S. was prepared. The preliminary list contained more than 95 items. However, the manufacturers indicated that some of these admixtures had been discontinued, and others were being marketed under different names.

IDENTIFICATION AND EVALUATION OF TEST PROCEDURES

The most common and widely used procedures for evaluating the effectiveness of air-entraining admixtures in the U.S. are the ones described in AASHTO Specifications M 154 and T157. These are equivalent to ASTM C 260, "Standard Specification for Air-Entraining Admixtures for Concrete" and ASTM C 233, "Standard Test Method for Air-Entraining Admixtures for Concrete," respectively.

The requirements of AASHTO M 154 can be divided into two types, uniformity requirements and performance requirements.

Uniformity. These requirements have been established to assure the purchaser that the manufacturer is implementing adequate quality control of production of the admixtures. These tests include pH measurement to check the relative acidity of the solution, air content of mortar prepared with the tested admixtures (ASTM C 185) and residue after oven drying. The acceptable range of pH should differ by no more than 2 points. The air should not vary by more than ±2 percentage points between successive lots and residue should not vary by more than ±12% of midpoint of limits supplied by manufacturer

Performance. The performance requirement calls for preparing concrete mixes using the tested air-entraining admixtures and comparing its mechanical properties with those of a reference concrete prepared using neutralized Vinsol resin, ASTM Type I cement and well-graded aggregate under controlled laboratory conditions. The compressive and flexural strengths at ages of 3, 7, and 28 days and 6 and 12 months should not be less than 90% of that of the reference concrete. The maximum shrinkage should not exceed 120% of the reference concrete and the durability factor (freeze-thaw test, AASHTO T161) should not be less than 80%.

The current uniformity tests are adequate to check the quality control of production of the admixtures. However, because of the increased number of air-entraining admixtures on the market and the lack of information on the source, type or basic ingredients of such admixtures, chemical analysis can be a helpful quality control test. Infrared analysis, for example can be used to identify chemical compounds in the admixtures. Chemists consider the data of such analyses as a "fingerprint" of an admixture. Infrared or other chemical analyses needed to identify such harmful elements may be added to the efficacy tests.

With respect to performance requirements, the concept of comparing the tested air-entraining admixtures with Vinsol resin, which has good performance records, is a valid procedure. These tests have been widely used in the industry in the U.S. since their introduction to AASHTO and ASTM in 1978. It appears, however, that although most of the newly introduced admixtures have compared favorably in these tests with Vinsol resin, some of these admixtures have shown poor field performance such as reduction in strength or poor durability. We believe that testing these admixtures according to current protocols and under ideal laboratory conditions is not enough to identify problems that may occur in the field. It is clear that field conditions and construction practices contribute to the problem, and have not been taken into account in standard materials testing. The coalescence of air-voids around aggregate particles, for instance, has been correlated with mixing time, hot weather and cement composition (low alkali) and conditions of aggregates, but would not normally be evident in standard acceptance testing of the admixture. Although AASHTO T157 allows the option of testing the air using the same materials that will be used in the field, such materials are still brought to the laboratory and tested under standardized conditions. For example, if the maximum size of coarse aggregate is greater than 1 in., the freshly mixed concrete shall be screened over a 1-in. sieve prior to fabricating the tested specimens.

Another shortcoming of standard admixture acceptance testing is the absence of an evaluation of the air-void system in hardened concrete (ASTM C 457). While the durability of the hardened concrete is inferred from the results of the 8-to-12-week-long freeze-thaw test (AASHTO T161), failure to observe microscopically the nature of the air-void system denies the insight to admixture performance, and may deny early warning of problems like air-void coalescence and clustering. The argument of the ASTM C 260 committee for not including C 457 analysis was the relatively high variation in the measurements of air-void parameters. The committee indicated that this test can lead to rejection of some of the admixtures based on a spacing factor value limits, yet these admixtures can pass the ASTM C 666 freeze-thaw test. With regard to the issue of the availability of Vinsol resin, the committee was searching for an alternative product. Air-entraining agent based on abietic acid to be used as a reference was proposed. The claim was that this product performs similarly to Vinsol resin. However, the committee decided not to accept it based on the argument that it "raise the air-void quality bar" relative to NVR for candidate AEAs.

Some European countries have different philosophies regarding admixture acceptance. For example, the efficacy test for new air-entraining admixtures in Germany is done only on cement paste and mortar. The time of setting of air-entrained and non-air-entrained mortars and cement paste is compared. In addition, the soundness of cement paste entrained with the tested admixture is measured. For the performance test, it is required that trial mixes be done using the same materials that will be used in the field, including the air-entraining admixture. The properties of the fresh and hardened concrete should meet the specified limits. These tests are usually carried out at ready-mixed concrete plants. Other European countries have similar specifications. However, starting last year most European countries, including Germany and Great Britain, will follow the European Standard.

The European Standard EN 934, "Admixtures for Concrete, Mortar and Grout", treats air-entraining admixtures similarly to other chemical admixtures in the evaluation process. They test all chemical admixtures in a manner similar to ASTM C 494 procedures "Standard Specification for Chemical Admixtures for Concrete," with the exception of acceptance testing for air-entraining admixtures. The standard is based on comparing concrete made with the tested air-entraining admixture with similar non air-entrained concrete. The specifications require that the air content of the reference concrete should be 2% or less and the air content of tested concrete should be between 4 and 6%. Compressive strength of the air-entrained concrete should be 75% or more of that of reference concrete at the age of 28 days. It is required that the spacing factor should be less than 0.20 mm. Again, as with the ASTM and AASHTO standards, concrete should be prepared under ideal laboratory conditions using well-graded aggregates and standard cements. Therefore, it is likely that most admixtures that pass the ASTM and AASHTO standards will easily be accepted under EN 934.

As mentioned above, AASHTO Specifications M 154 and T 157 (ASTM C 260 and C 233) are the most commonly used procedures. All state DOTs require that any new air-entraining admixtures be evaluated according to AASHTO Specifications M 154 and T 157 (ASTM C 260 and C 233). Materials laboratories at DOTs used to conduct their own evaluation of new air-entraining admixtures. However, now all states require that certification of the new admixtures be provided by the suppliers. Some states require the certification to be conducted by an independent laboratory. The materials engineers at the state DOTs recognize that certified admixtures may not perform adequately under adverse field conditions or when certain admixtures or cementations materials are used in concrete. The state of Indiana, for example requires the repetition of the performance (physical) tests if high-range water reducer is to be used in the concrete.

Results of air-entraining admixture approval tests were collected mainly from the DOT admixture manufacturers and materials laboratories. All these reports were for certified admixtures. As shown in these reports, performance of the tested admixtures was comparable with the performance of Vinsol resin admixture under ideal conditions, even though some of these admixtures were reported to have poor performance in the field in certain instances.

The state of Delaware provided us with their strength study data conducted on two air-entraining admixtures, namely MB AE 90 and MB VR. MB-AE is described by the manufacturer as natural wood rosin admixture and MB-VR is a natural Vinsol resin. Variations in strength exist between two approved admixtures, especially when water reducer is used.

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APPENDIX B

Foam Drainage and Infrared Test Results

TABLE B-1 ALPHA OLEFIN SULFONATE ADMIXTURES (WATER TEST)

	Tested without cement							
	Foam Drainage Statistics				Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
320240 N	231.7	399.2	0.807	74.7	960.0	900.0	830.0	745.0
Admixture ES	**238.0**	**314.6**	**0.886**	**76.8**	**740.0**	**710.0**	**670.0**	**620.0**
Admixture C	**301.8**	**770.9**	**0.942**	**97.3**	**910.0**	**870.0**	**810.0**	**760.0**
320240 OO	276.2	292.2	0.859	89.1	920.0	850.0	820.0	780.0
Admixture EA	**240.8**	**241.2**	**0.758**	**77.7**	**870.0**	**825.0**	**800.0**	**780.0**
320240 TT	238.0	230.9	0.768	76.8	880.0	850.0	830.0	820.0

TABLE B- 2 ALPHA OLEFIN SULFONATE ADMIXTURES (WATER + CEMENT TEST)

	Tested with cement							
	Foam Drainage Statistics				Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
320240 N	272.7	307.5	0.853	88.0	700.0	570.0	530.0	310.0
Admixture ES	**262.3**	**254.8**	**0.949**	**84.6**	**520.0**	**480.0**	**400.0**	**310.0**
Admixture C	**276.4**	**338.2**	**0.835**	**89.2**	**720.0**	**630.0**	**570.0**	**540.0**
320240 OO	274.7	261.5	0.849	88.6	700.0	570.0	550.0	550.0
Admixture EA	**235.7**	**49.2**	**0.427**	**76.0**	**620.0**	**580.0**	**430.0**	**400.0**
320240 TT	275.8	299.5	0.874	89.0	680.0	500.0	440.0	390.0

TABLE B-3 BENZENE SULFONATE ADMIXTURES (WATER TEST)

	Tested without cement							
	Foam Drainage Statistics				Foam Height			
Admixture	V_0	-1/k	r^2	% drained	Initial	15 min	30 min	60 min
Admixture B	**284.4**	**299.6**	**0.901**	**91.7**	**720.0**	**680.0**	**660.0**	**660.0**
320240 EE	281.9	58.4	0.976	90.9	430.0	400.0	350.0	340.0
320240 PP	262.6	7.8	0.943	84.7	400.0	390.0	370.0	345.0
320240 Z	299.3	139.4	0.967	96.5	---	---	---	---

TABLE B-4 BENZENE SULFONATE ADMIXTURES (WATER + CEMENT TEST)

	Tested with cement							
	Foam Drainage Statistics				Foam Height			
Admixture	V_0	-1/k	r^2	% drained	Initial	15 min	30 min	60 min
Admixture B	**297.1**	**89.5**	**0.906**	**95.9**	**520.0**	**425.0**	**350.0**	**330.0**
320240 EE	256.6	67.4	0.963	82.8	480.0	470.0	470.0	465.0
320240 PP	257.5	68.7	0.989	83.1	480.0	470.0	460.0	450.0
320240 Z	234.7	147.6	0.967	75.7	---	---	---	---

TABLE B-5 RESIN/ROSIN AND FATTY ACIDS ADMIXTURES (WATER TEST)

	Tested without cement							
					Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
320240 R	265.9	9.1	0.947	85.8	370.0	311.0	310.0	310.0
320240 NN	310.6	7.4	0.711	100.2				
320240 H	290.9	311.6	0.914	93.8	660.0	560.0	380.0	330.0
Admixture ED	**276.0**	**32.0**	**0.988**	**89.0**	**440.0**	**390.0**	**380.0**	**340.0**
320240 GG	278.4	25.1	0.902	89.8	410.0	400.0	395.0	380.0
320240 JJ	253.7	125.7	0.750	81.8	0.0	0.0	500.0	380.0
320240 DD	277.3	313.1	0.864	89.5	740.0	650.0	500.0	405.0
320240 T	287.1	16.2	0.931	92.6	450.0	400.0	375.0	320.0
Admixture M	**287.0**	**409.8**	**0.926**	**92.6**	**800.0**	**720.0**	**540.0**	**460.0**
320240 VV	291.1	183.1	0.880	93.9	430.0	390.0	340.0	320.0
320240 ZZ	315.7	46.2	0.809	101.8	330.0	320.0	310.0	310.0
Admixture S	**300.6**	**0.2**	**0.048**	**97.0**	**310.0**	**310.0**	**310.0**	**310.0**
320240 BBB	288.7	41.9	0.945	93.1	0.0	0.0	0.0	0.0

TABLE B-6 RESIN/ROSIN AND FATTY ACIDS ADMIXTURES (WATER + CEMENT TEST)

	Tested with cement							
	Foam Drainage Statistics				Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
320240 R	249.3	32.4	0.961	80.4	375.0	350.0	350.0	350.0
320240 NN	266.6	146.5	0.928	86.0				
320240 H	275.3	32.7	0.832	88.8	450.0	440.0	430.0	420.0
Admixture ED	**235.1**	**59.9**	**0.830**	**75.8**	**470.0**	**460.0**	**455.0**	**455.0**
320240 GG	214.2	36.2	0.772	69.1	480.0	460.0	460.0	460.0
320240 JJ	267.1	19.3	0.899	86.1	390.0	390.0	380.0	375.0
320240 DD	283.7	6.5	0.733	91.5	370.0	360.0	360.0	350.0
320240 T	258.5	81.8	0.985	83.4	550.0	450.0	450.0	450.0
Admixture M	**291.5**	**17.3**	**0.923**	**94.0**	**400.0**	**390.0**	**390.0**	**390.0**
320240 VV	279.3	25.6	0.934	90.1	450.0	400.0	440.0	390.0
320240 ZZ	281.3	38.9	0.954	90.7	430.0	430.0	440.0	420.0
Admixture S	**191.8**	**27.2**	**0.859**	**61.9**	**580.0**	**580.0**	**440.0**	**565.0**
320240 BBB	231.7	67.3	0.952	74.7	0.0	0.0	440.0	0.0

TABLE B-7 COMBINATION ADMIXTURES (WATER TEST)

	Tested without cement							
	Foam Drainage Statistics				Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
320240 P	318.6	320.3	0.932	102.8	430.0	350.0	340.0	325.0
320240 G	297.0	302.9	0.915	95.8	670.0	600.0	590.0	570.0
320240 I	305.8	324.1	0.907	98.7	530.0	450.0	370.0	320.0
320240 B	291.3	297.9	0.920	94.0	600.0	560.0	510.0	400.0

TABLE B-8 COMBINATION ADMIXTURES (WATER + CEMENT TEST)

	Tested with cement							
	Foam Drainage Statistics				Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
320240 P	278.7	9.7	0.975	89.9	400.0	380.0	380.0	375.0
320240 G	289.3	39.3	0.822	93.3	540.0	450.0	370.0	330.0
320240 I	272.9	21.7	0.905	88.0	420.0	410.0	410.0	410.0
320240 B	287.5	41.1	0.996	92.8	400.0	390.0	385.0	370.0

TABLE B-9 VINSOL RESIN ADMIXTURES (WATER TEST)

	Tested without cement							
	Foam Drainage Statistics				Foam Height			
Admixture	**V_0**	**-1/k**	**r^2**	**% drained**	**Initial**	**15 min**	**30 min**	**60 min**
Admixture EI	**304.1**	**4.4**	**0.382**	**98.1**	**310**	**310**	**310**	**310**
Admixture E	**300.2**	**321.0**	**0.922**	**96.8**	**590**	**400**	**330**	**320**
320240 J	305.7	259.2	0.982	98.6	500	430	340	320
320240 D	304.6	284.3	0.983	98.3	550	410	350	330
Admixture D	301.3	13.1	0.740	97.2	370	320	315	310
320240 S	286.1	298.2	0.928	92.3	660	540	500	450
320240 W	297.7	316.7	0.912	96.0	---	---	---	---
320240 SS	277.9	291.8	0.920	89.6	630	600	520	460
Admixture EM	**280.2**	**267.7**	**0.950**	**90.4**	**620**	**560**	**530**	**520**
320240 AA	313.8	245.3	0.791	101.2	---	---	---	---
320240 BB	287.8	296.5	0.940	92.8	---	---	---	---
320240 UU	0.0	262.0	0.979	0.0	315	312	310	310
320240 YY	291.1	311.2	0.920	93.9	680	530	450	390
320240 CCC	296.2	194.4	0.977	95.6	450	330	315	305
320240 HH	295.8	323.9	0.875	95.4	500.0	370.0	350.0	330.0

TABLE B-10 VINSOL RESIN ADMIXTURES (WATER + CEMENT TEST)

	Tested with cement							
	Foam Drainage Statistics				Foam Height			
Admixture	V_0	-1/k	r^2	% drained	Initial	15 min	30 min	60 min
Admixture EI	**234.6**	**144.0**	**0.916**	**75.7**	**550**	**550**	**540**	**530**
Admixture E	**173.0**	**45.3**	**0.916**	**55.8**	**630**	**630**	**630**	**630**
320240 J	204.6	228.7	0.888	66.0	650	630	600	600
320240 D	219.2	276.7	0.927	70.7	630	620	615	610
Admixture D	239.5	158.4	0.880	77.3	580	375	375	375
320240 S	15.1	0.5	0.396	4.9	700	695	695	695
320240 W	234.2	48.9	0.926	75.5	---	---	---	---
320240 SS	0.1	0.2	0.044	0.0	730	730	730	730
Admixture EM	**122.2**	**150.3**	**0.549**	**39.4**	**725**	**720**	**720**	**720**
320240 AA	223.8	34.2	0.292	72.2	---	---	---	---
320240 BB	18.8	35.4	0.114	6.1	---	---	---	---
320240 UU	210.3	165.2	0.801	67.8	570	570	560	560
320240 YY	159.5	1210.5	0.908	51.4	680	670	670	670
320240 CCC	238.3	171.0	0.890	76.9	580	410	360	330
320240 HH	274.5	49.5	0.963	88.6	410.0	405.0	400.0	380.0

ALPHA OLEFIN SULFONATE ADMIXTURES

National Cooperative Highway Research Program
NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

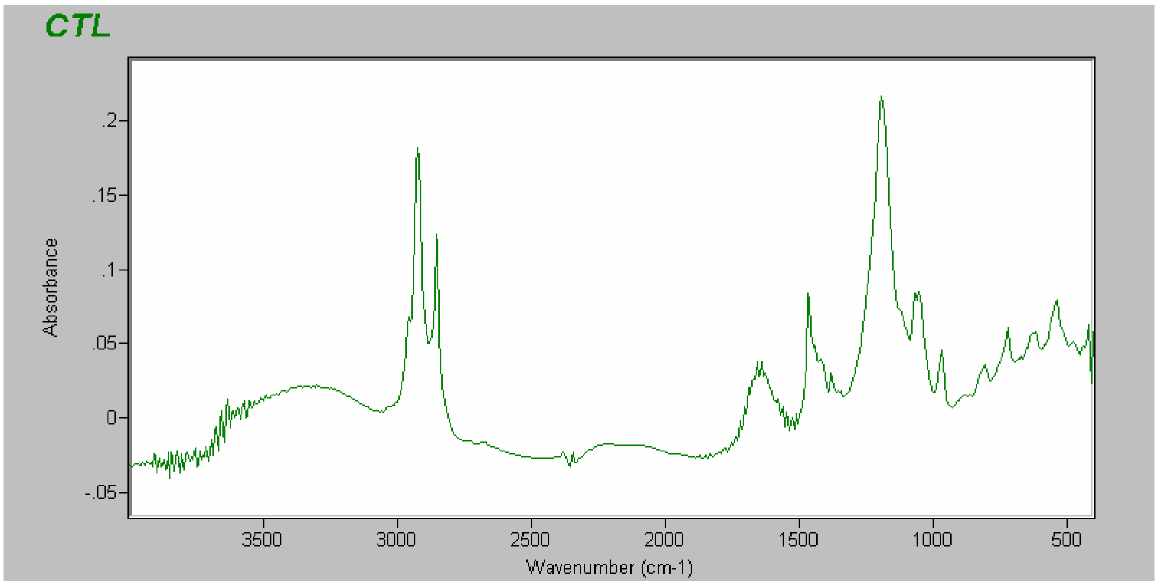
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240N

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.8
Density	1.01
% Solids	6.66

The infrared spectrum is consistent with an air entraining admixture containing sodium olefin sulfonate.



National Cooperative Highway Research Program
NCHRP 18-10
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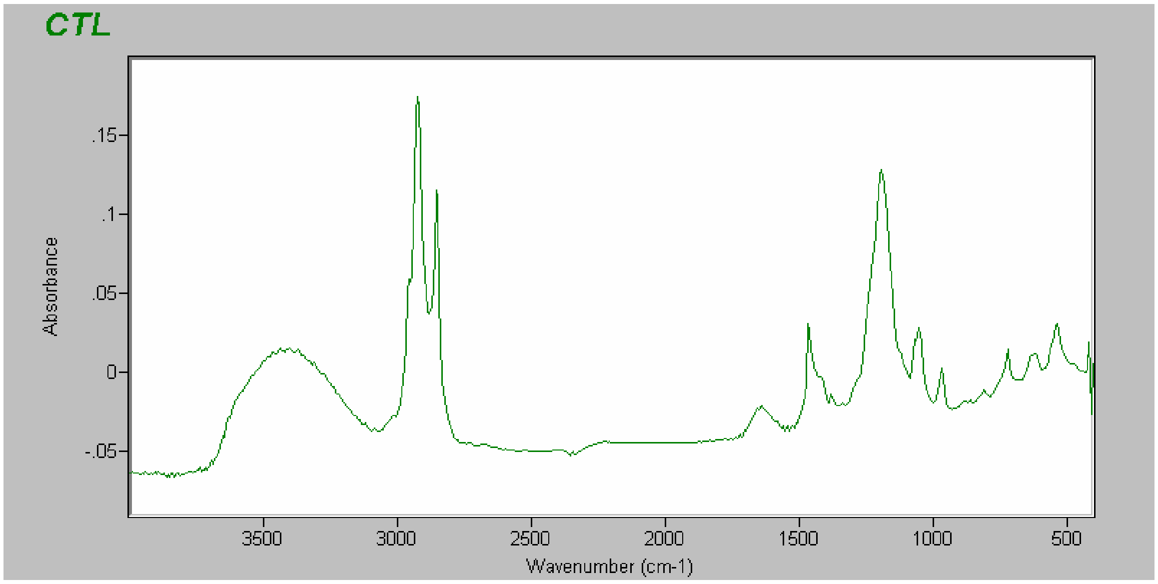
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE ES

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.4
Density	1.005
% Solids	3.42

The infrared spectrum is consistent with an air entraining admixture containing sodium olefin sulfonate.



National Cooperative Highway Research Program
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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

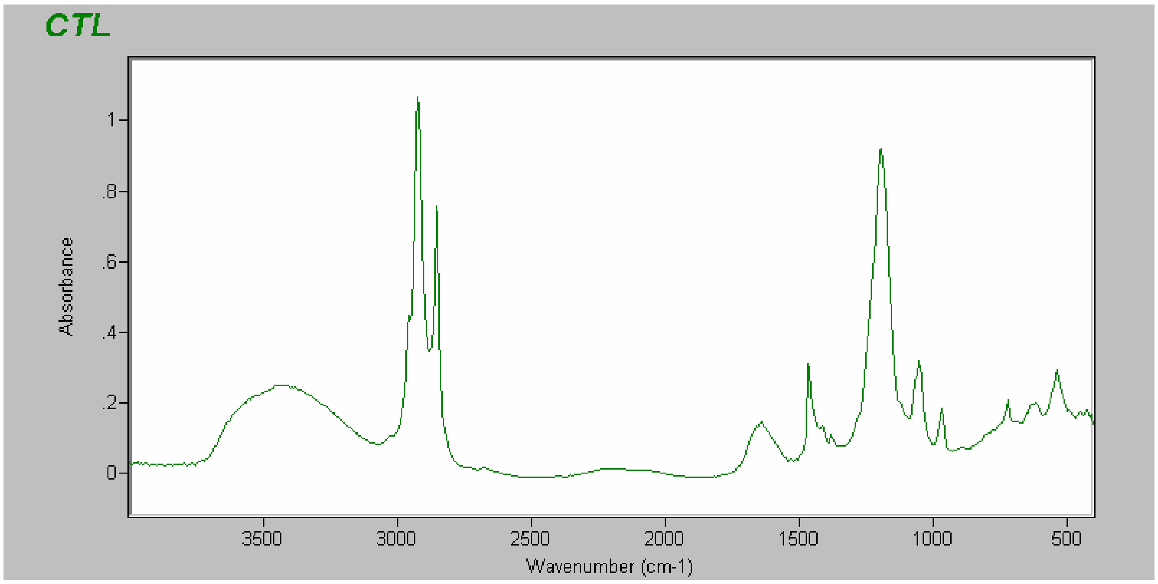
ADMIXTURE C

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.61
Density	1.015
% Solids	9.46

The infrared spectrum is consistent with an air entraining admixture containing surfactant and alkyl olefin sulfonate.



National Cooperative Highway Research Program
NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

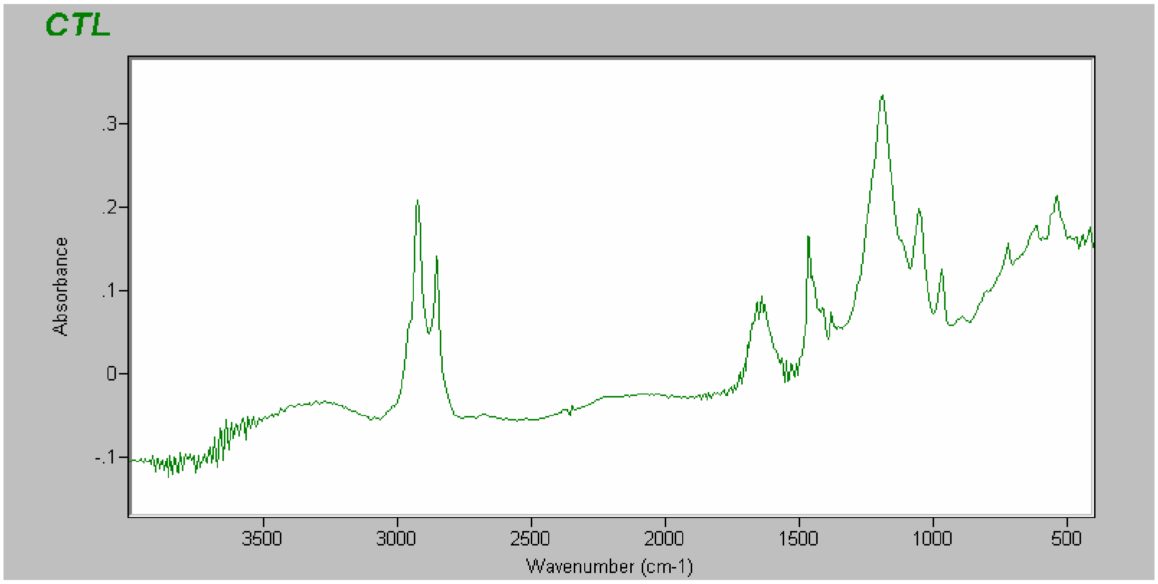
ADMIXTURE NO. 320240OO

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	6.92
Density	1.010
% Solids	4.79

The infrared spectrum is consistent with an air entraining admixture containing alpha olefin sulfonate.



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Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

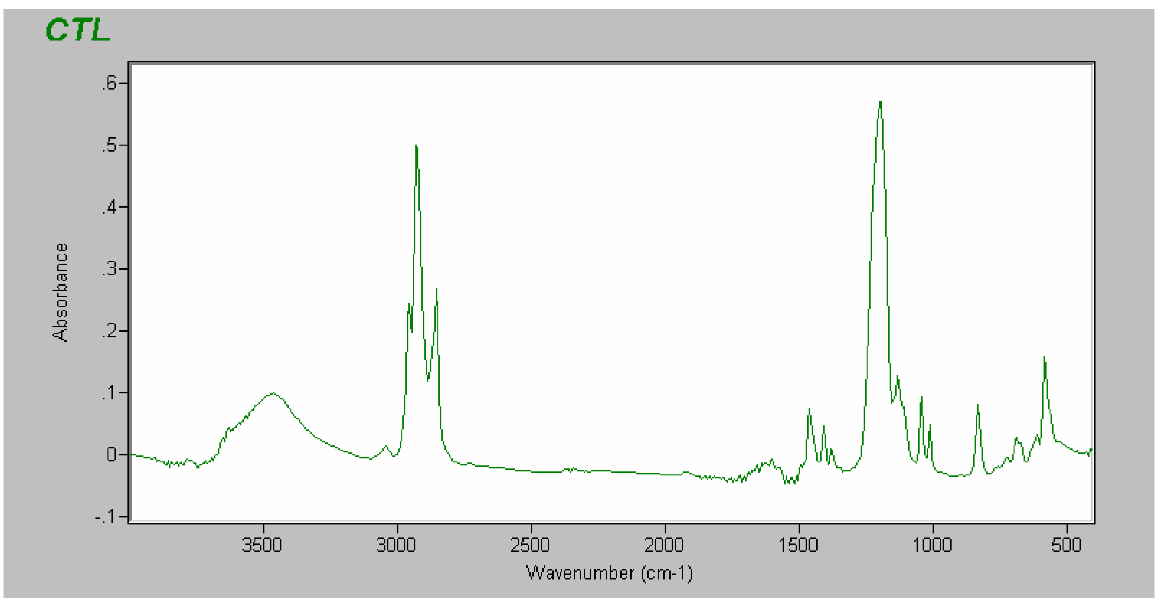
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE EA

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.74
Density	1.013
% Solids	5.60

The infrared spectrum is consistent with an air entraining admixture containing alphpoa olefin sulfonate.



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Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

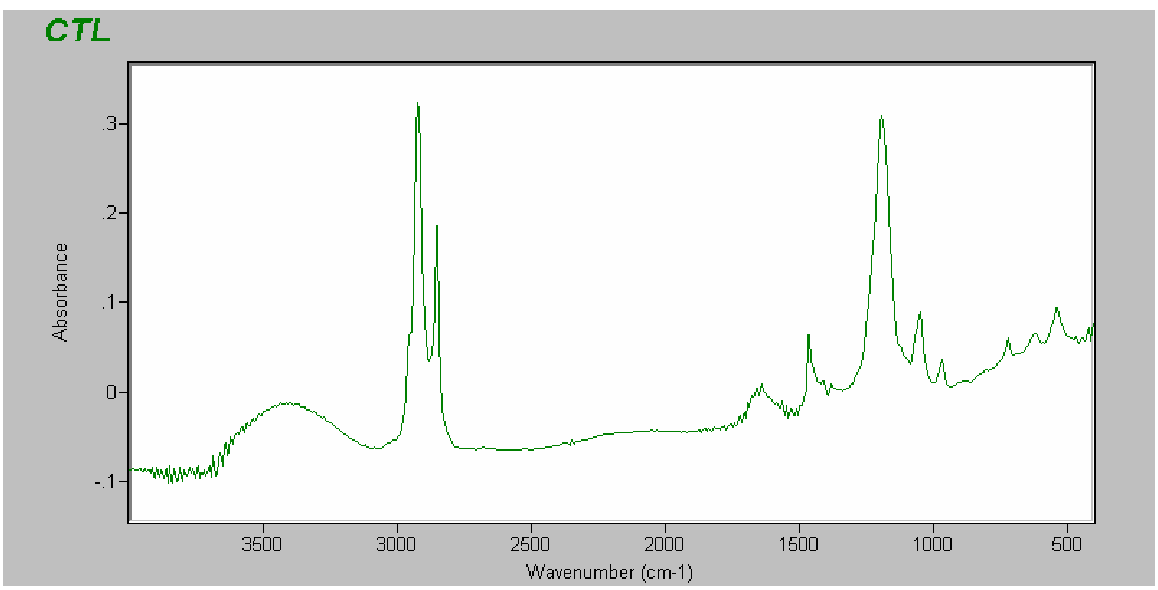
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240TT

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.18
Density	1.010
% Solids	4.47

The infrared spectrum is consistent with an air entraining admixture containing alpha olefin sulfonate.



BENEZENE SULFONATE ADMIXTURES

National Cooperative Highway Research Program
NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

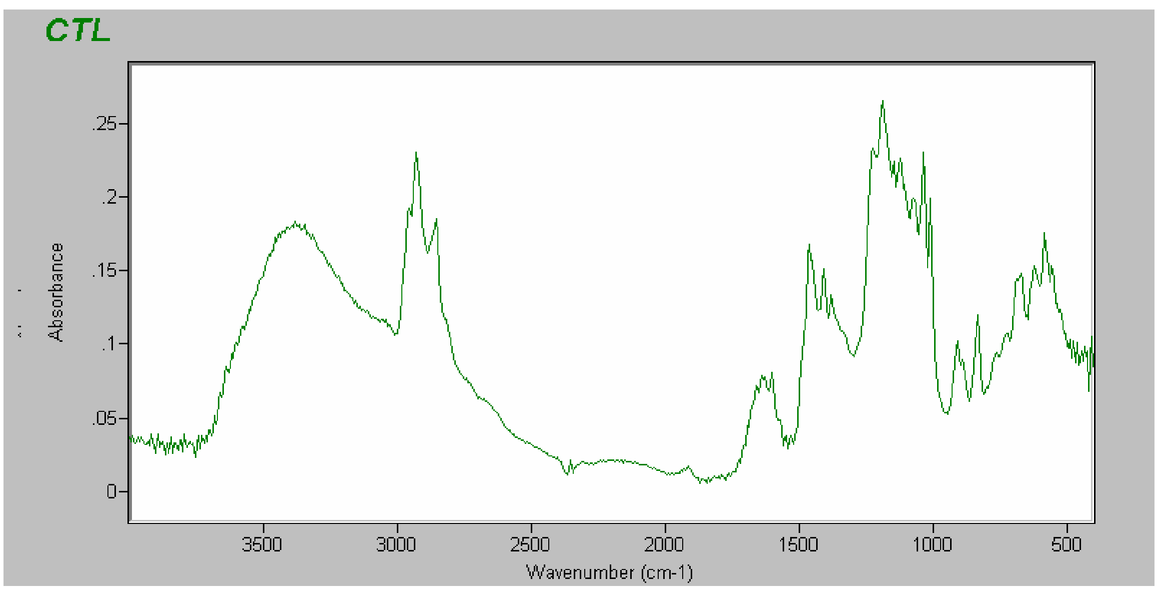
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE B

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.92
Density	1.015
% Solids	3.67

The infrared spectrum is consistent with an air entraining admixture containing benzyl sulfonate salt.



National Cooperative Highway Research Program
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Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

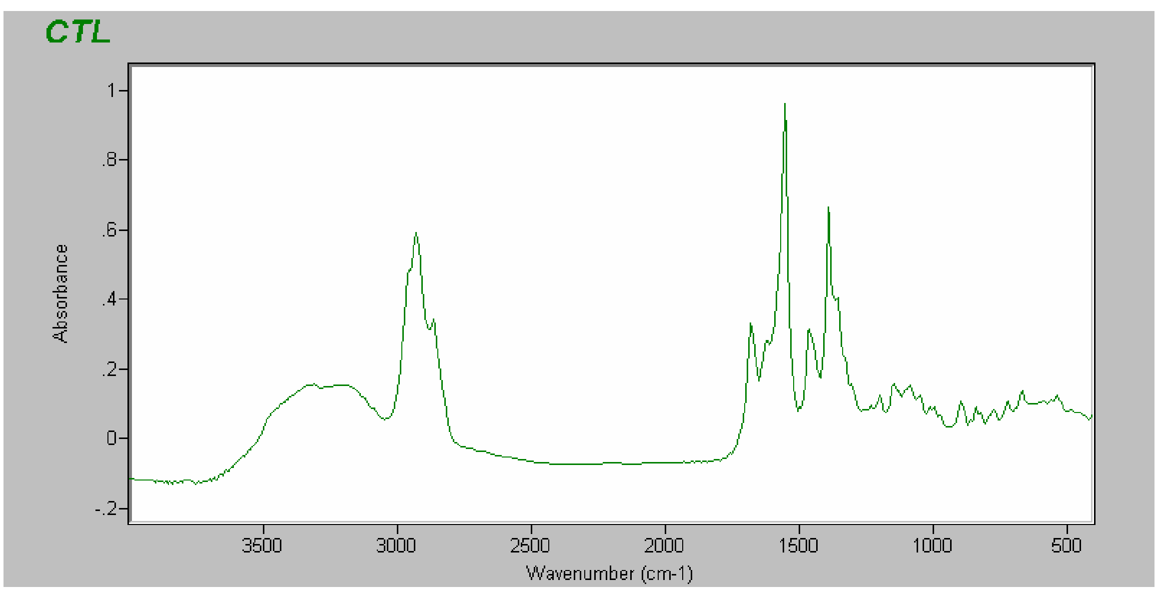
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240EE

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.18
Density	1.011
% Solids	6.04

The infrared spectrum is consistent with an air entraining admixture containing benzene sulfonate salt.



National Cooperative Highway Research Program
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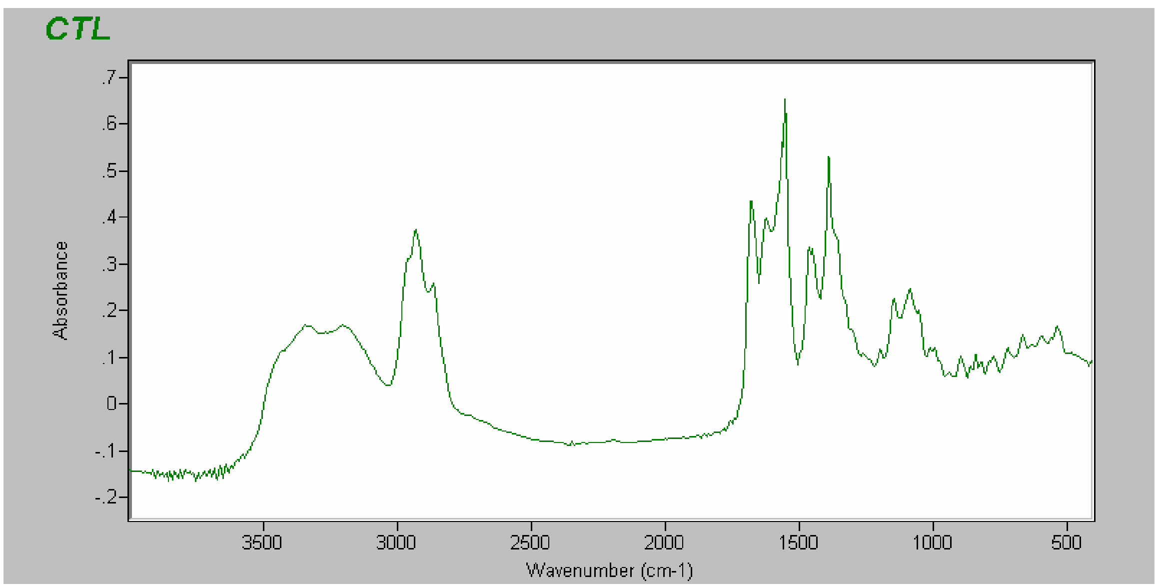
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240PP

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.48
Density	1.020
% Solids	6.58

The infrared spectrum is consistent with an air entraining admixture containing benzene sulfonate.



National Cooperative Highway Research Program
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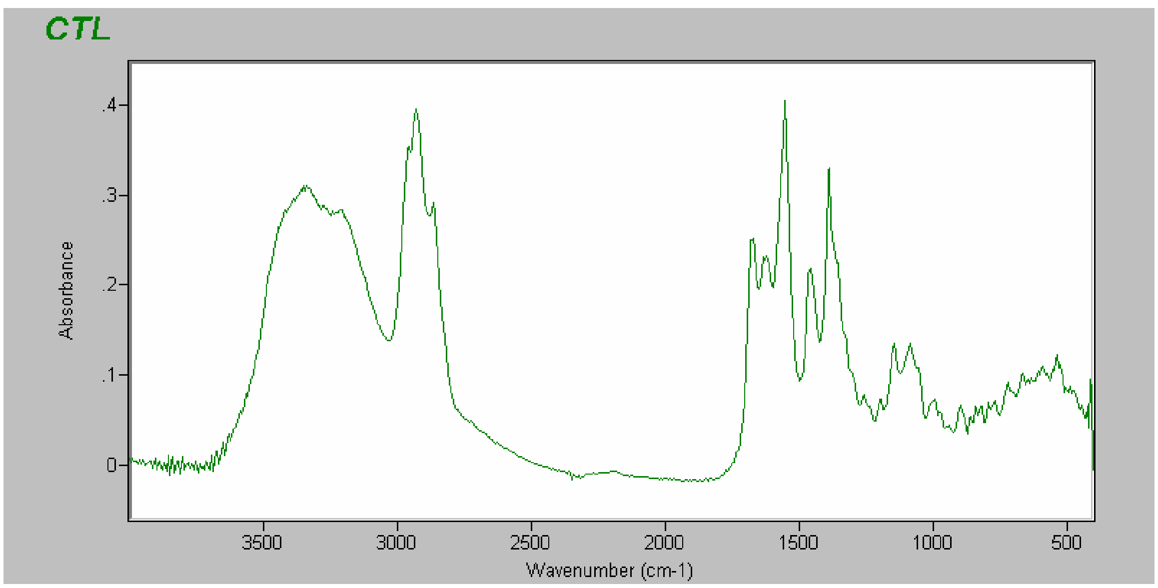
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240Z

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.24
Density	1.030
% Solids	12.19

The infrared spectrum is consistent with an air entraining admixture containing benzene sulfonate.



X ignores vinsol resin comment on FTIR spectrum.

RESIN/ROSIN AND FATTY ACIDS ADMIXTURES

National Cooperative Highway Research Program
NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

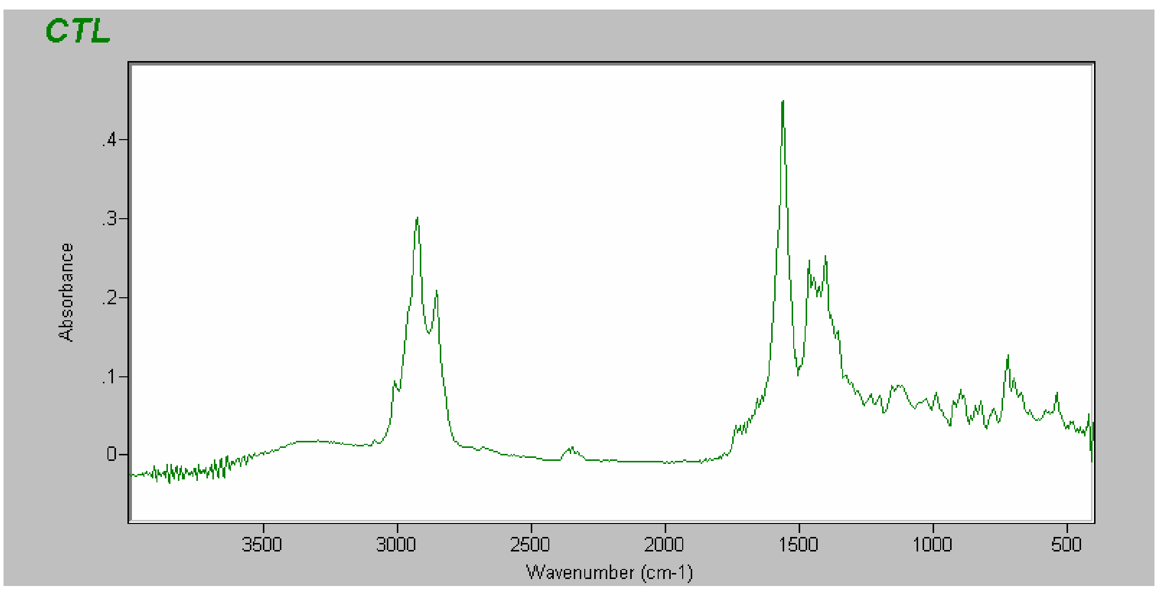
ADMIXTURE NO. 320240R

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.2
Density	1.010
% Solids	7.81

The infrared spectrum is consistent with an air entraining admixture containing sodium salt of tall oil.



National Cooperative Highway Research Program
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Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

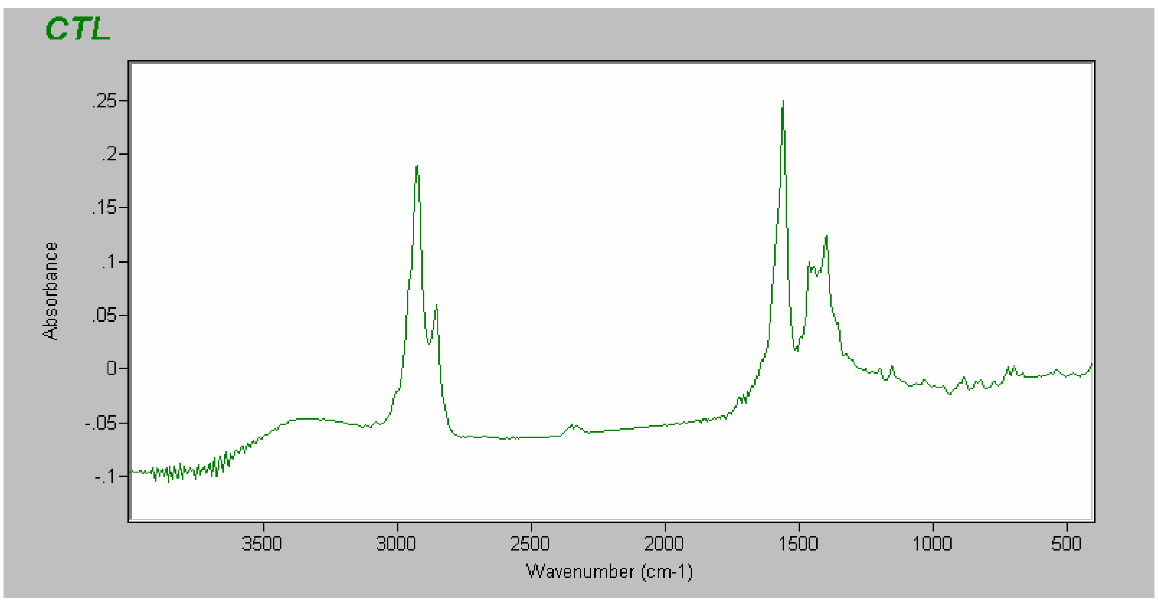
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240NN

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.25
Density	1.025
% Solids	10.67

The infrared spectrum is consistent with an air entraining admixture containing fatty acids.



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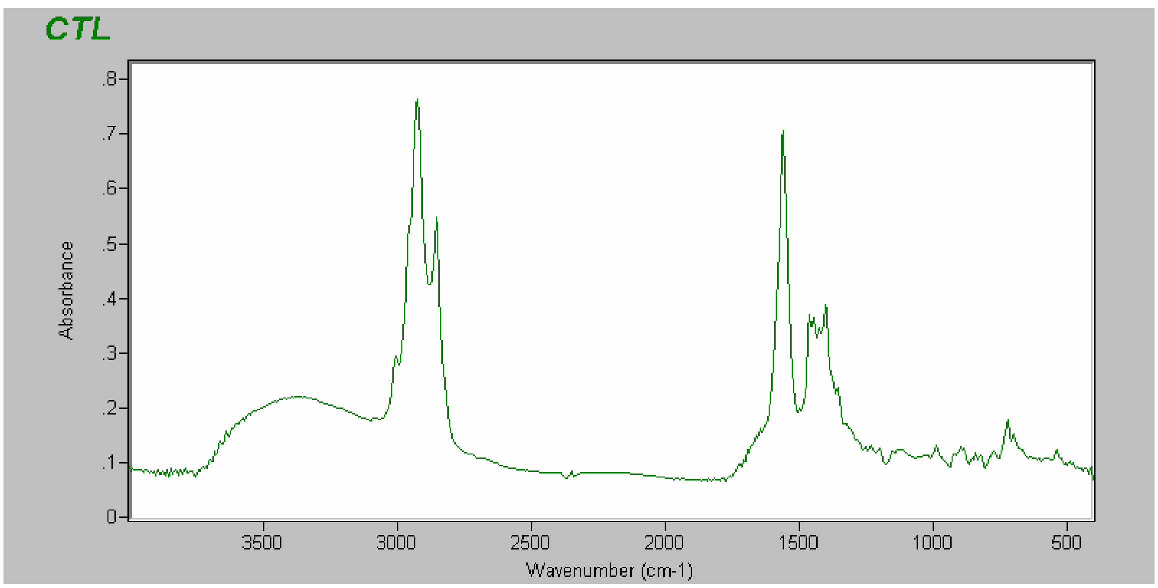
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240H

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.26
Density	1.015
% Solids	11.25

The infrared spectrum is consistent with an air entraining admixture containing modified resin and sodium salt of tall oil.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

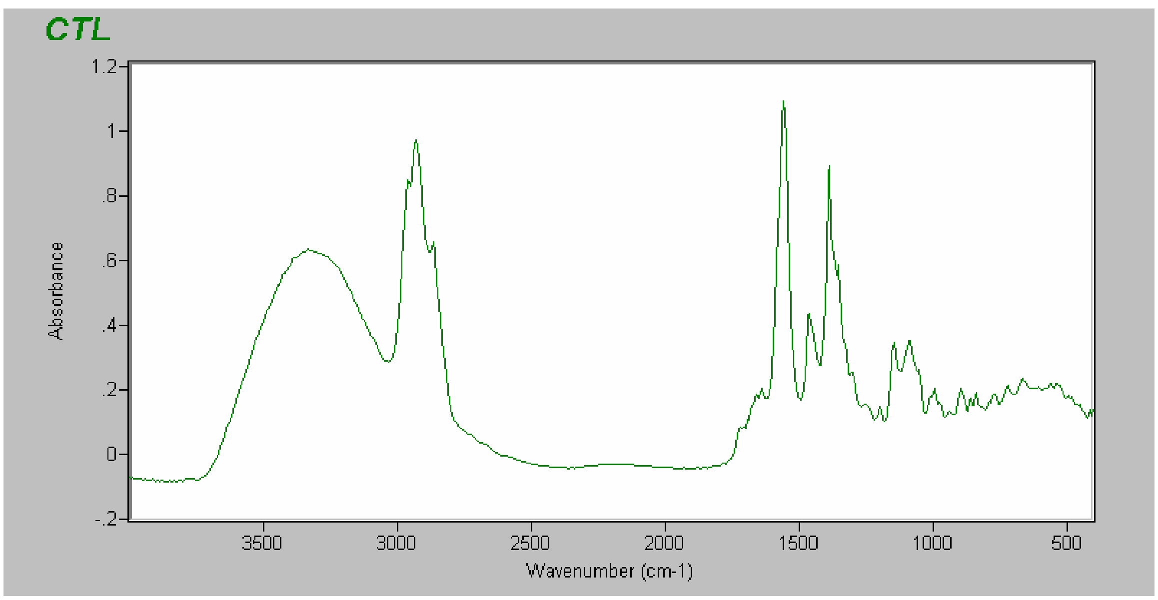
ADMIXTURE ED

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.89
Density	XXX
% Solids	4.89

The infrared spectrum is consistent with an air entraining admixture containing saponified rosin.



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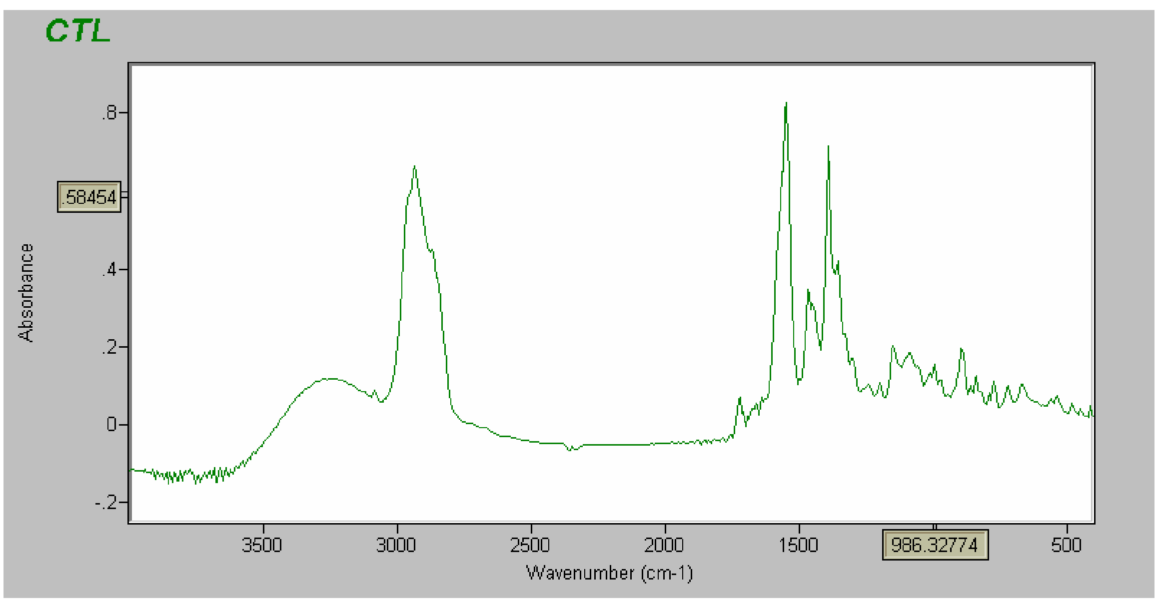
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240GG

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.75
Density	1.018
% Solids	6.99

The infrared spectrum is consistent with an air entraining admixture containing saponified rosin.



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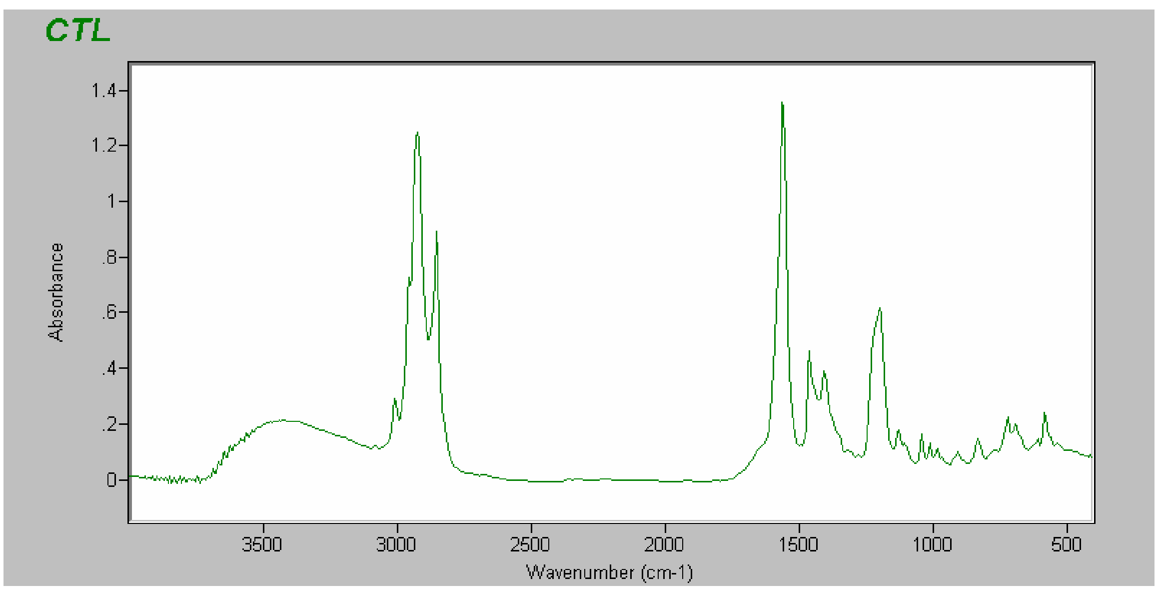
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240JJ

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.6
Density	1.015
% Solids	20.16

The infrared spectrum is consistent with an air entraining admixture containing fatty acid, fatty acid salts and benzene sulfonates.



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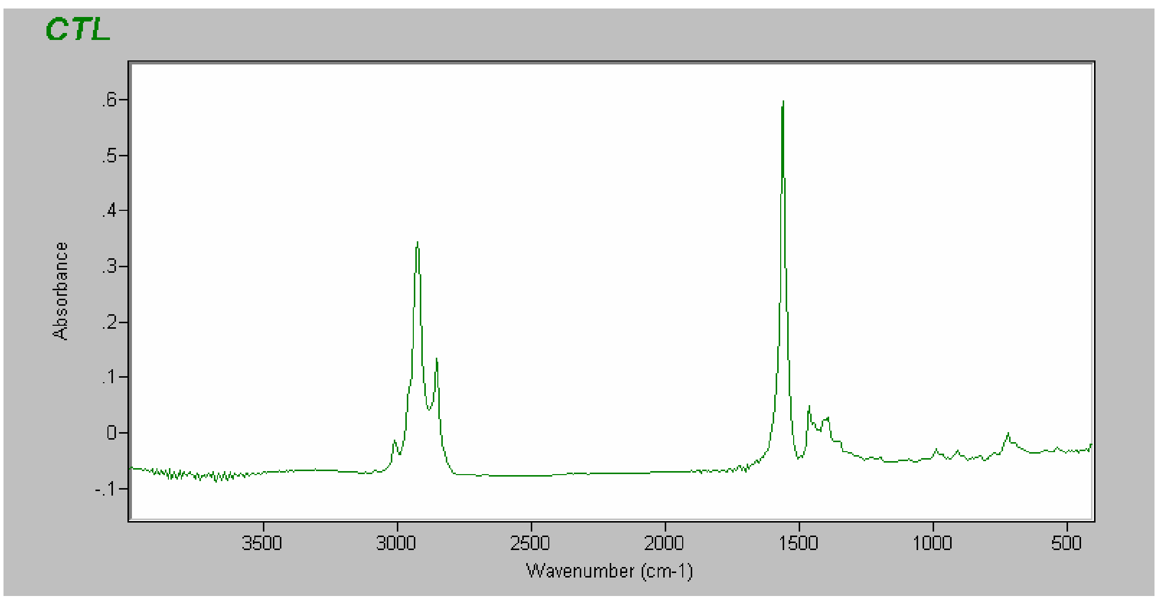
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240DD

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.99
Density	1.011
% Solids	10.59

The infrared spectrum is consistent with an air entraining admixture containing fatty acid salts.



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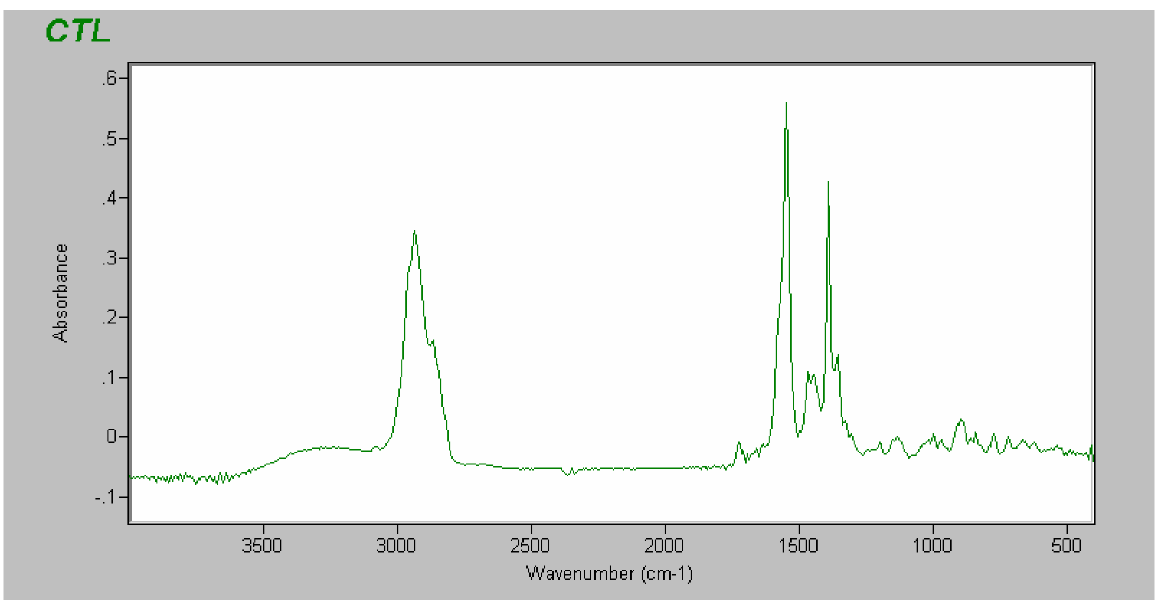
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240T

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.93
Density	1.015
% Solids	6.42

The infrared spectrum is consistent with an air entraining admixture containing gum rosin.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

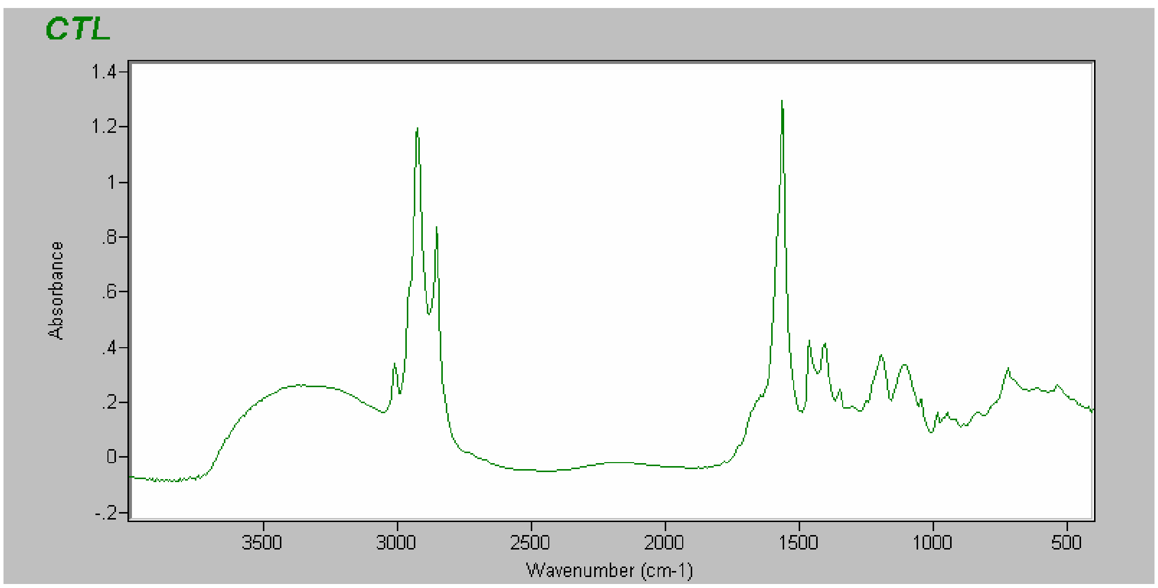
ADMIXTURE M

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.06
Density	1.015
% Solids	12.51

The infrared spectrum is consistent with an air entraining admixture containing fatty acids alpha olefin sulfonate and propylene glycol.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

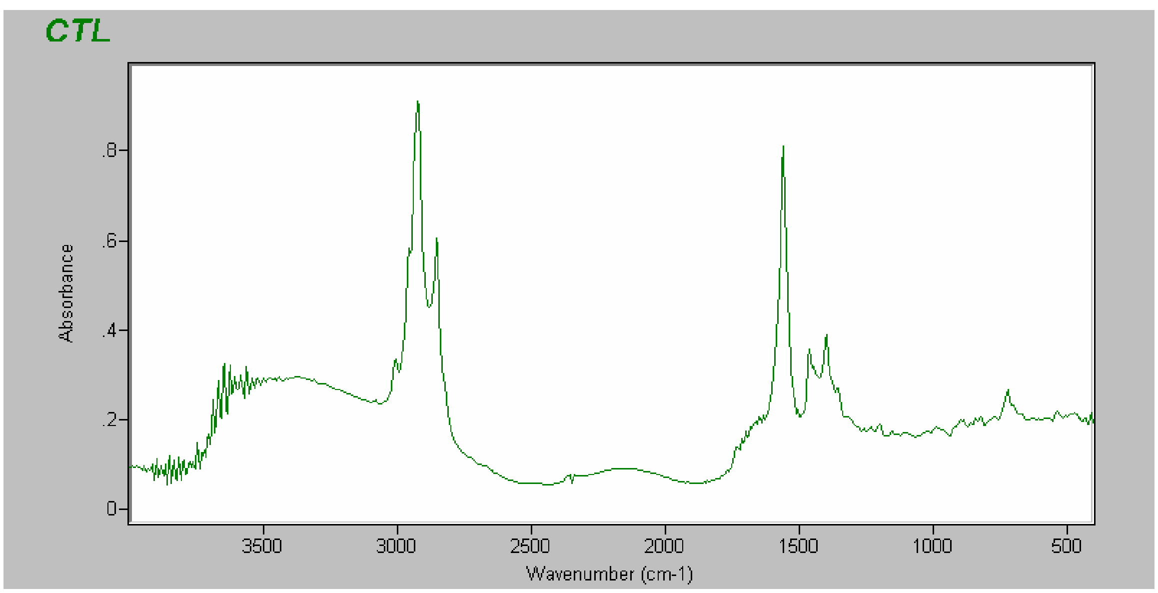
ADMIXTURE NO. 320240VV

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.48
Density	1.015
% Solids	9.98

The infrared spectrum is consistent with an air entraining admixture containing saponified rosin.



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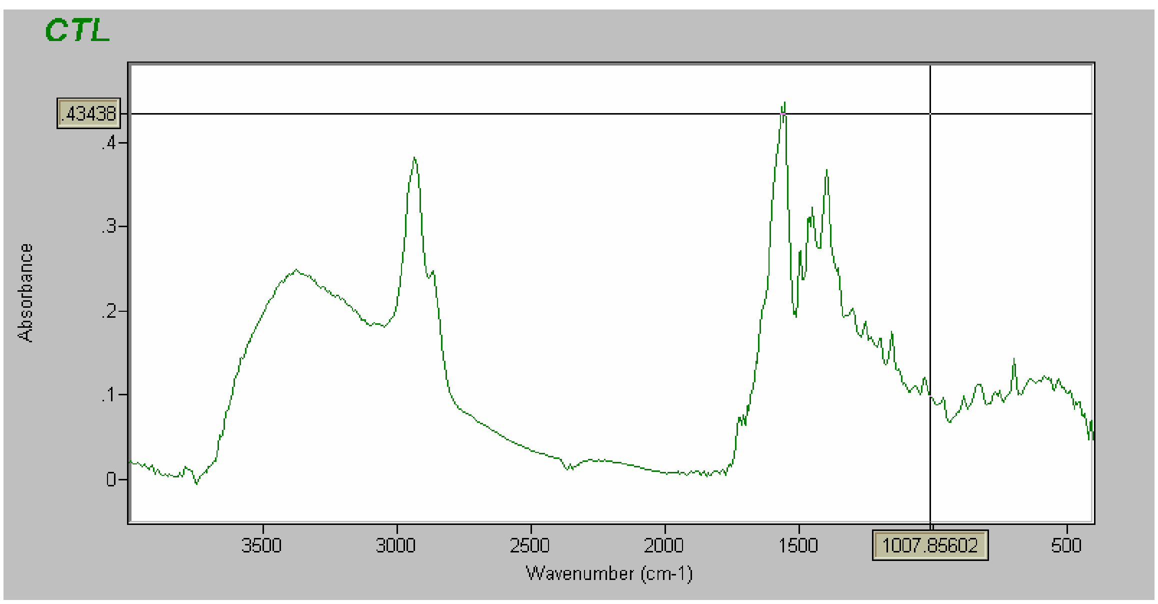
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240AA

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.79
Density	1.050
% Solids	16.94

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



December 20, 2003

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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

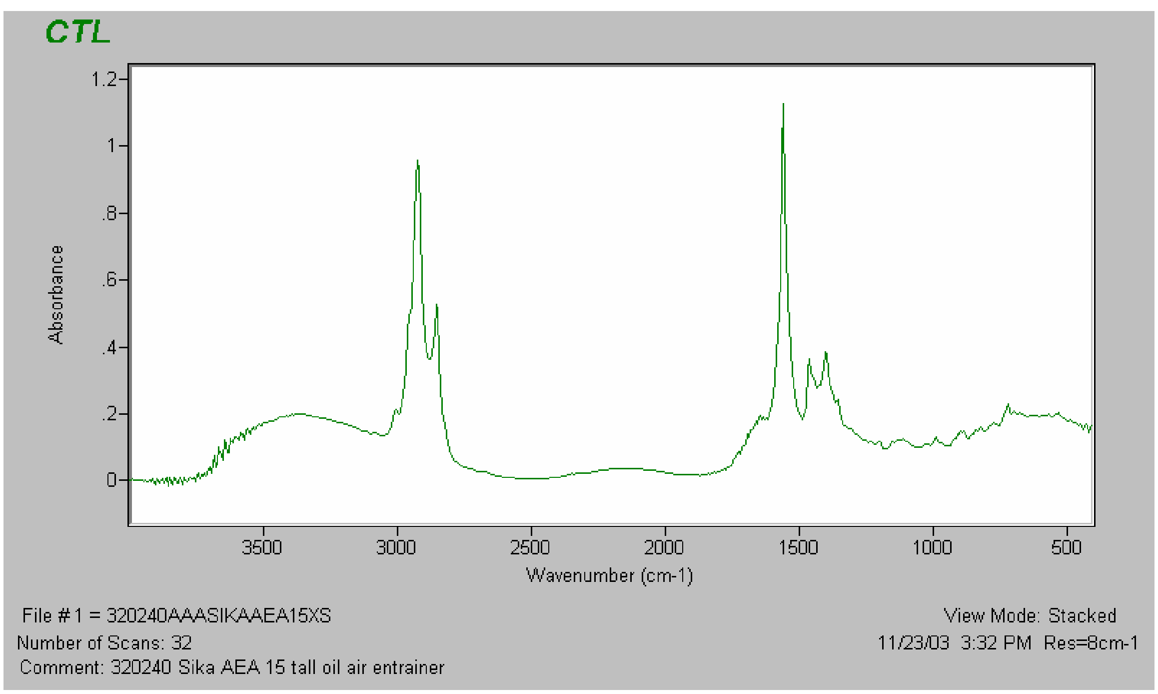
ADMIXTURE S

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.41
Density	1.045
% Solids	16.12

The infrared spectrum is consistent with an air entraining admixture containing rosin soap.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

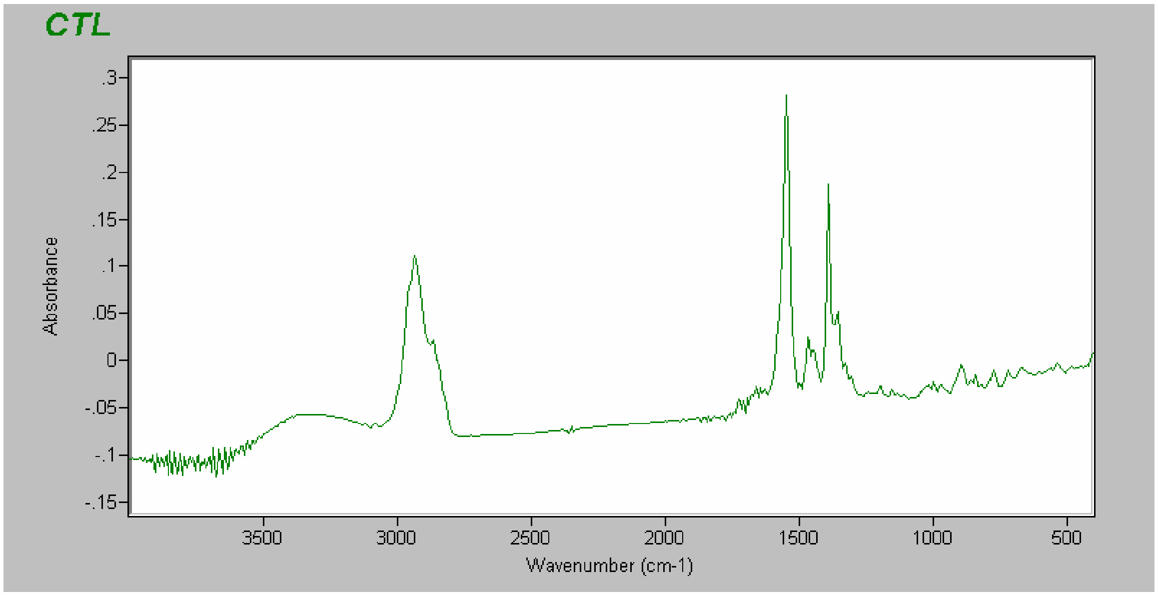
ADMIXTURE NO. 320240BBB

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.5
Density	1.010
% Solids	5.97

The infrared spectrum is consistent with an air entraining admixture containing resin soap.



COMBINATION ADMIXTURES

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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

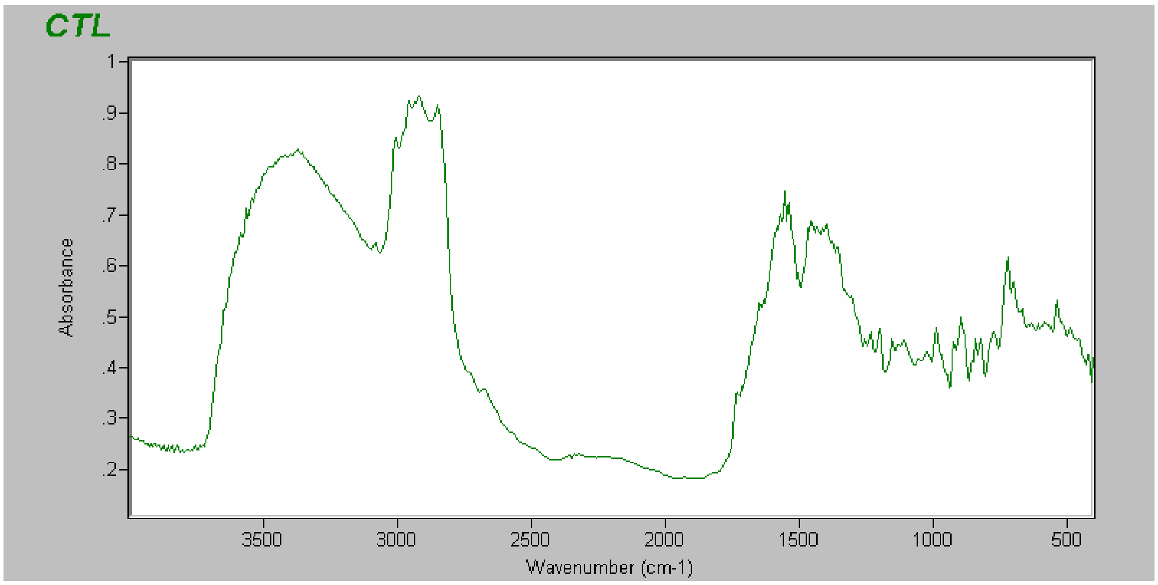
ADMIXTURE NO. 320240P

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.9
Density	1.015
% Solids	15.5

The infrared spectrum is consistent with an air entraining admixture containing modified rosins and fatty acids.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

ADMIXTURE NO. 320240G

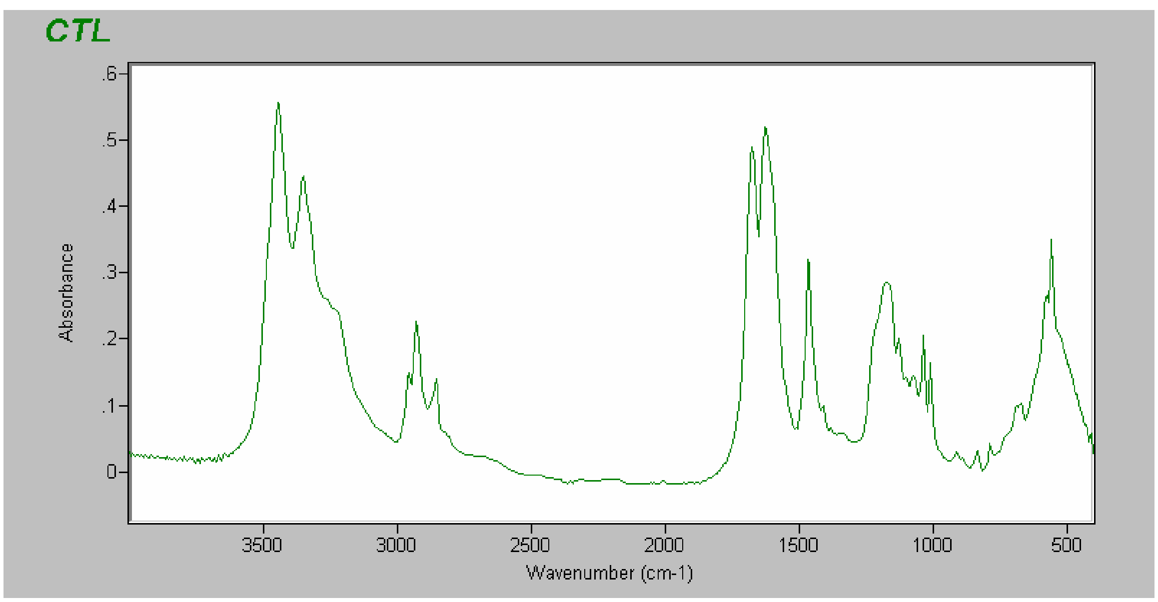
CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.79
Density	1.015
% Solids	6.01

The infrared spectrum is consistent with an air entraining admixture containing urea and benzene sulfonate.

FTIR Spectrum



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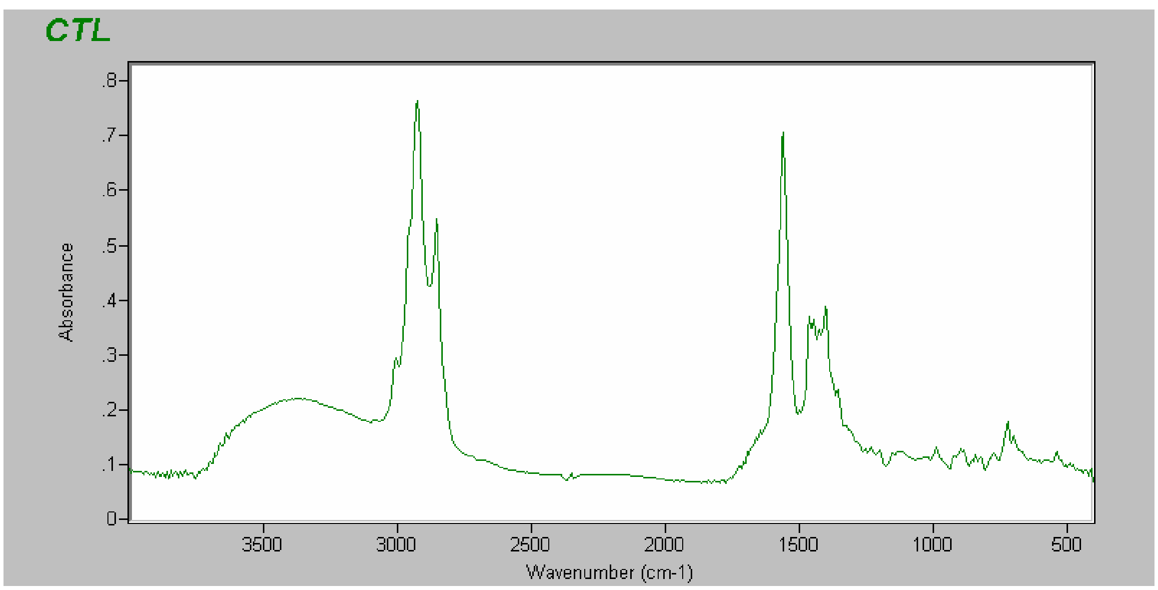
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240I

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	9.66
Density	1.015
% Solids	8.22

The infrared spectrum is consistent with an air entraining admixture containing surfactant and tall oil.



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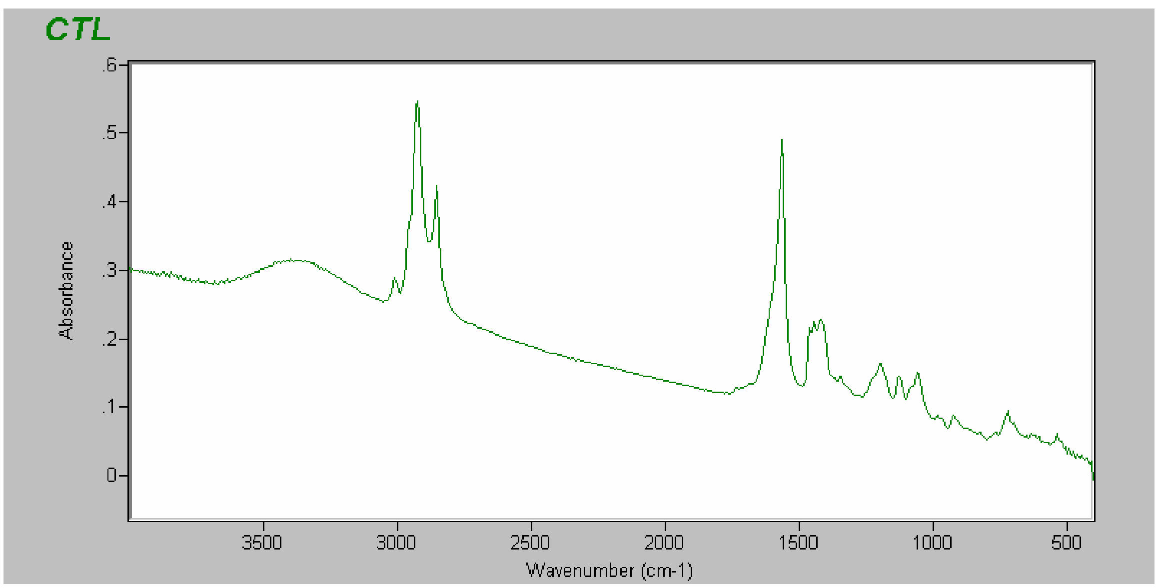
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240B

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	9.92
Density	1.020
% Solids	11.38

The infrared spectrum is consistent with an air entraining admixture containing surfactant and tall oil.



VINSOL RESIN ADMIXTURES

National Cooperative Highway Research Program
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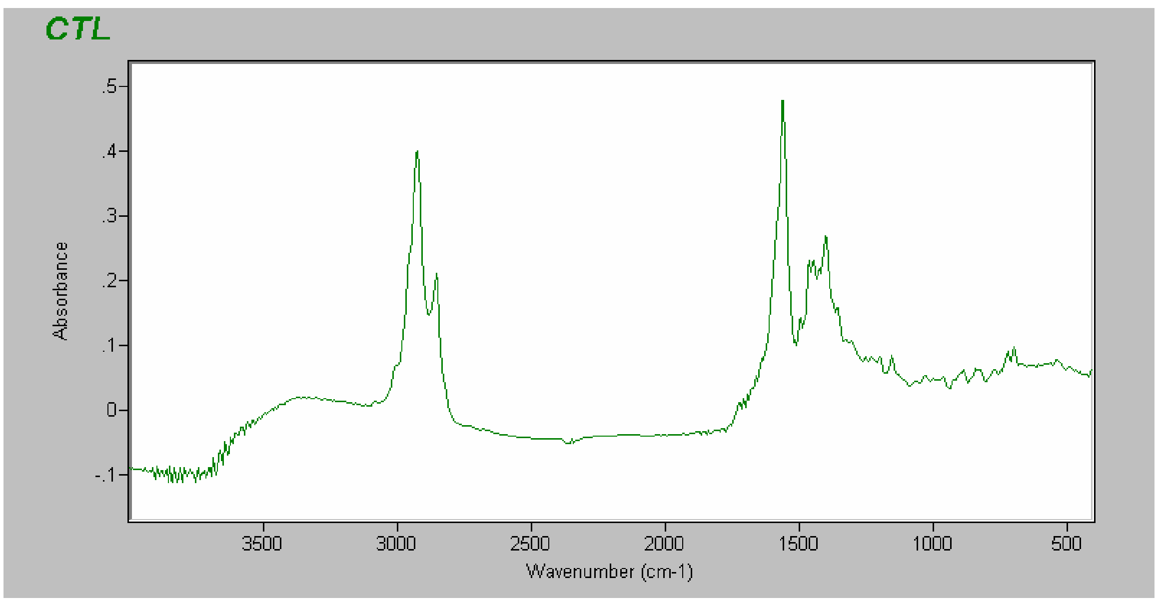
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE EI

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.61
Density	1.030
% Solids	13.29

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

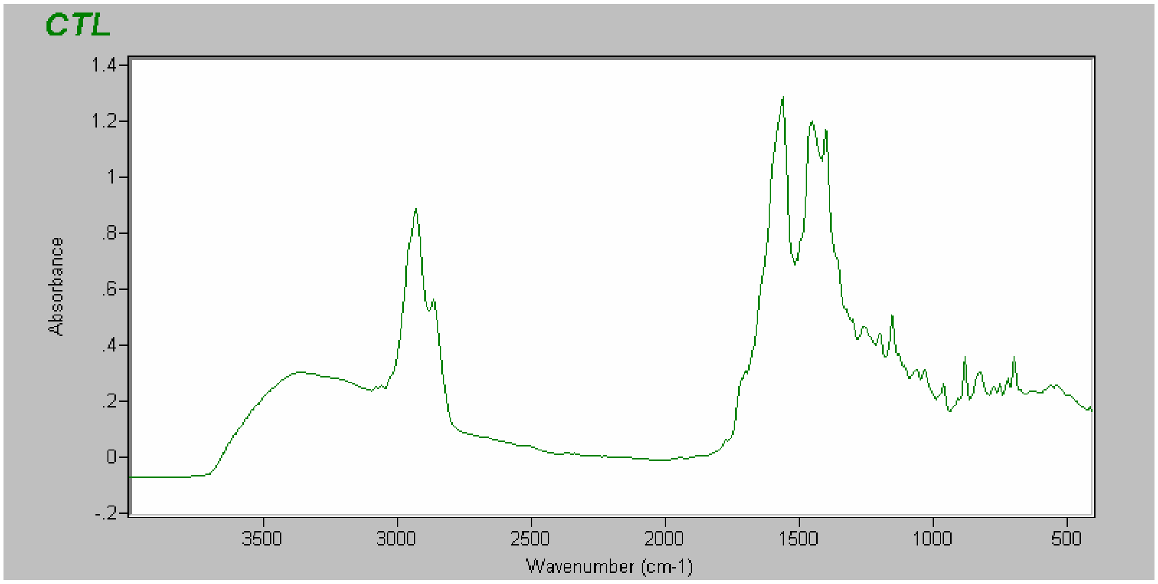
ADMIXTURE NO. 320240Q

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.2
Density	1.050
% Solids	16.2

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin.



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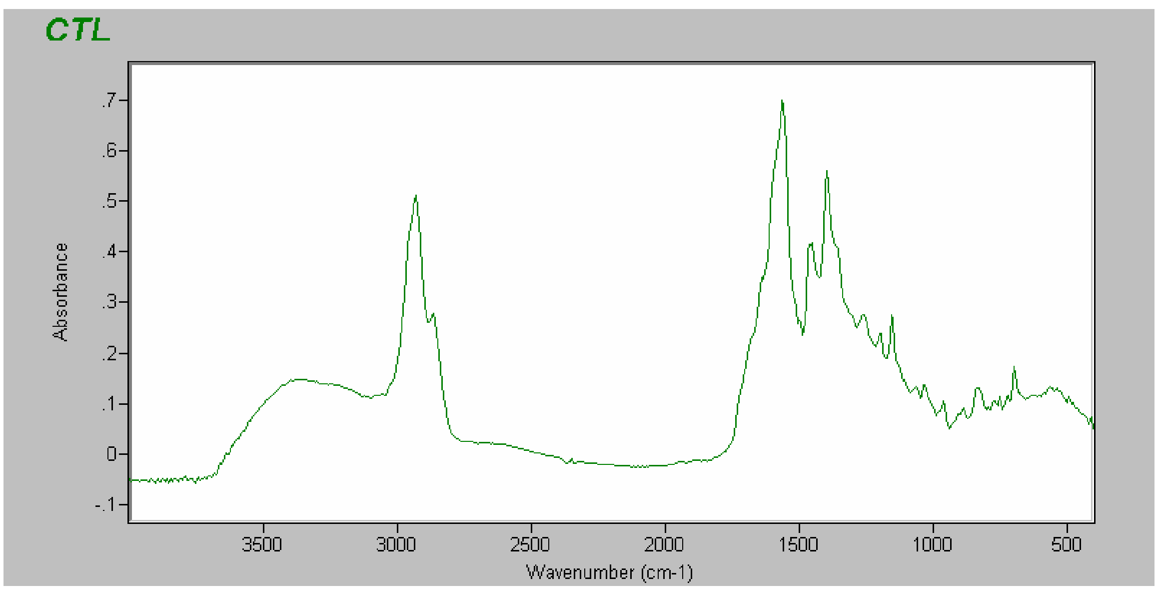
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240J

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	9.49
Density	1.035
% Solids	12.43

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin.



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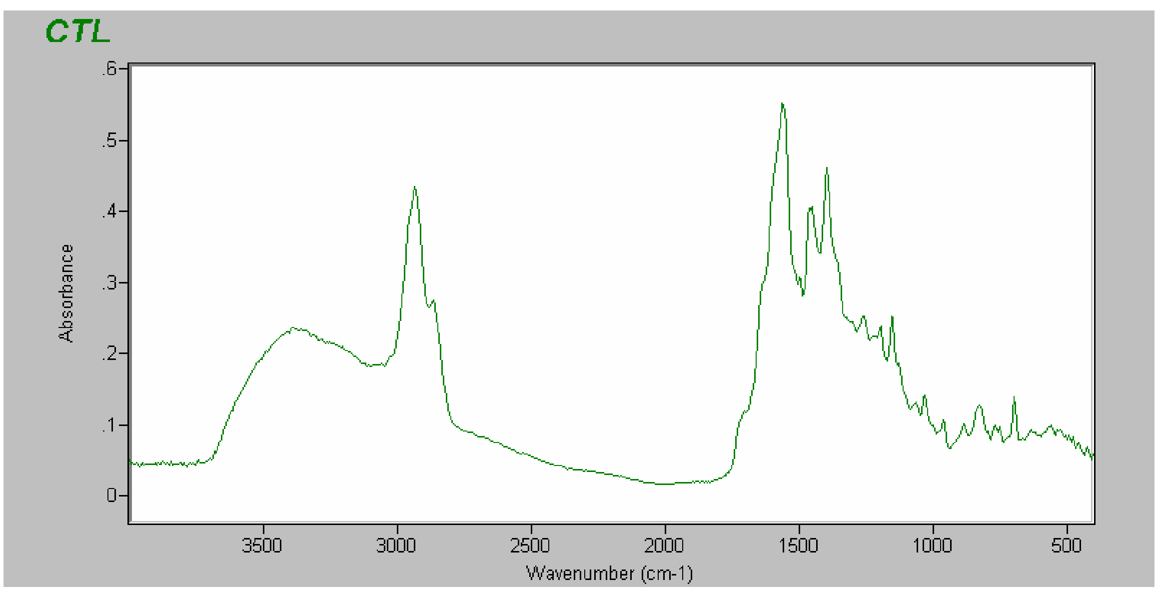
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240D

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.16
Density	1.030
% Solids	10.68

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

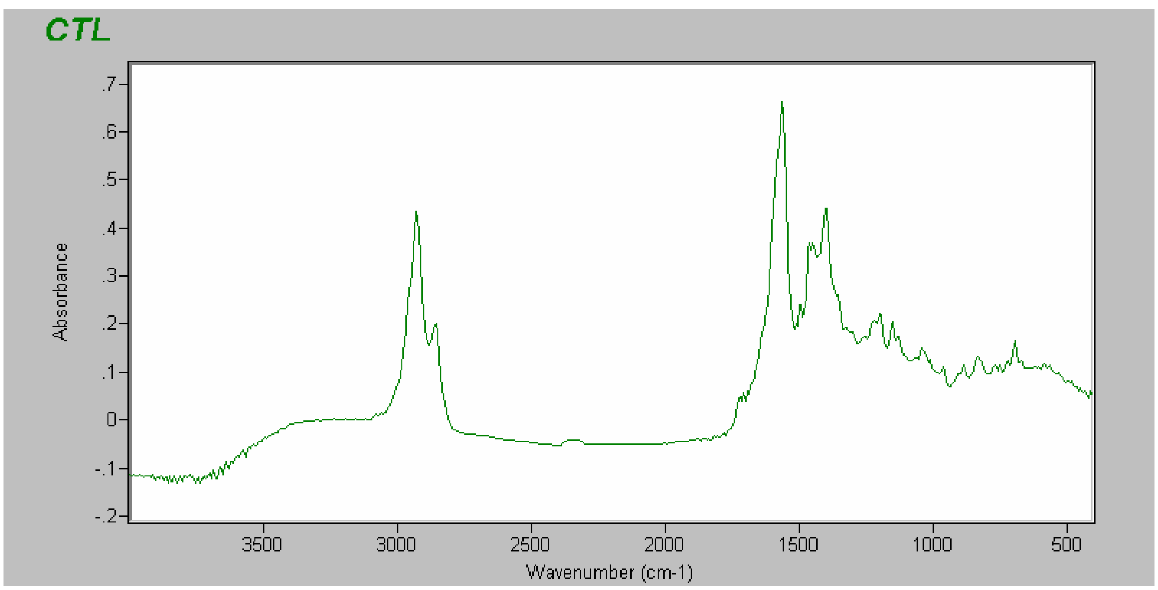
ADMIXTURE D

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.34
Density	1.030
% Solids	13.51

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin and rosin.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

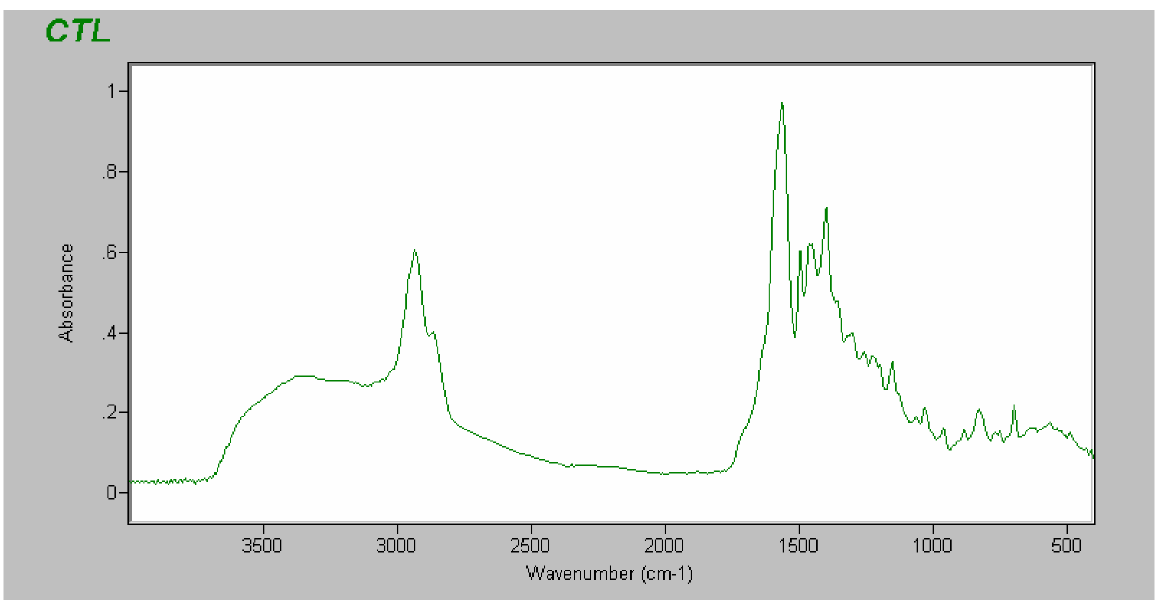
ADMIXTURE NO. 320240S

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.82
Density	1.055
% Solids	18.06

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

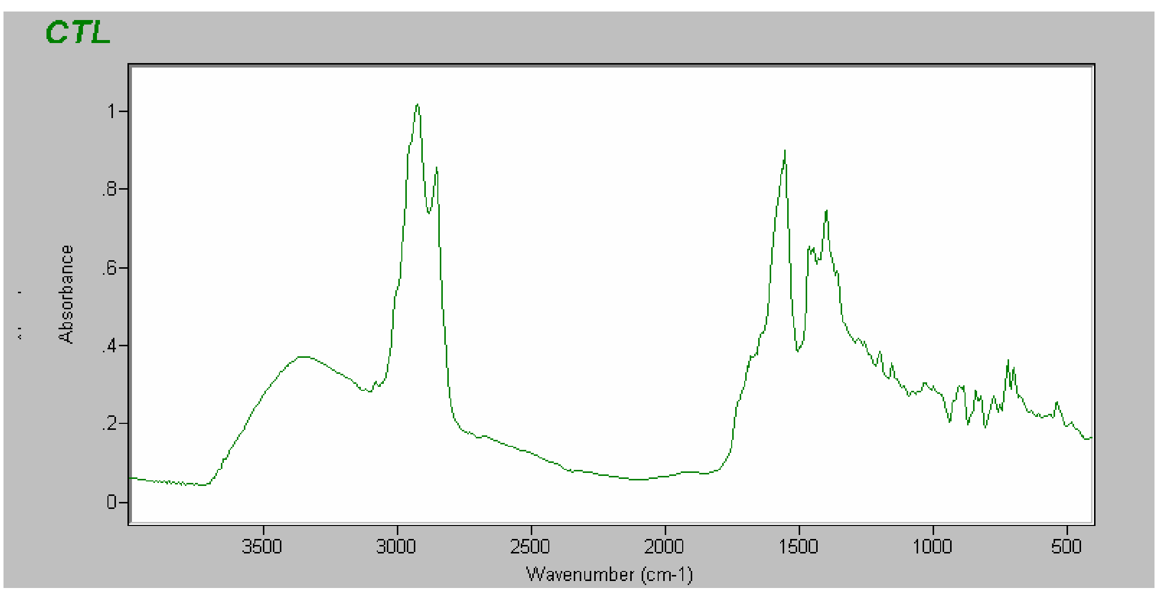
ADMIXTURE NO. 320240W

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	9.35
Density	1.030
% Solids	17.23

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin.



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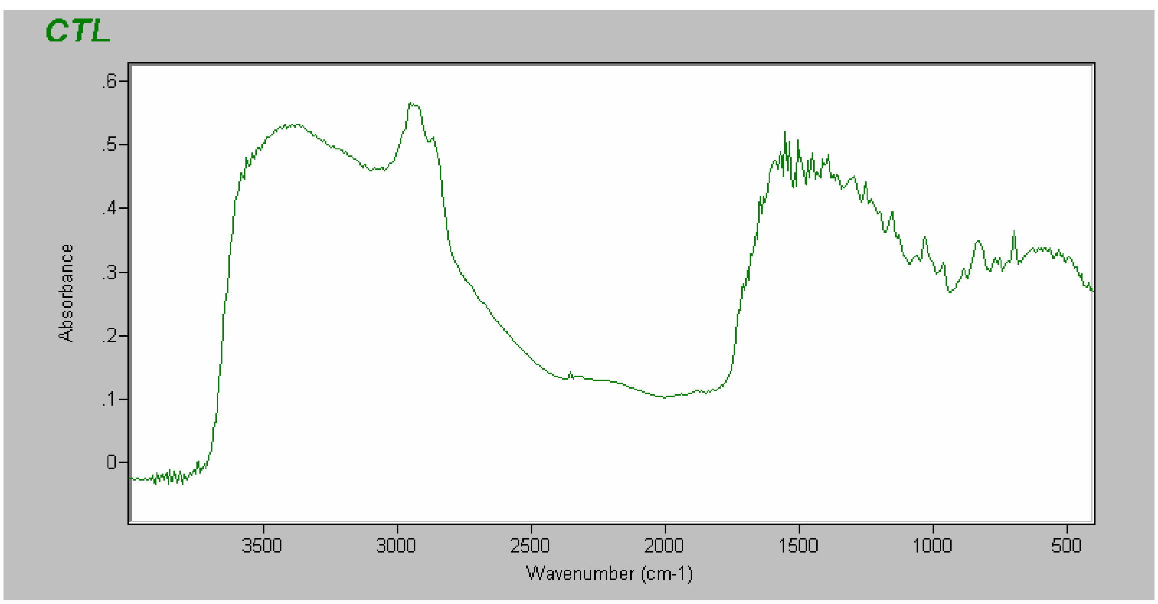
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240SS

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.89
Density	1.070
% Solids	22.46

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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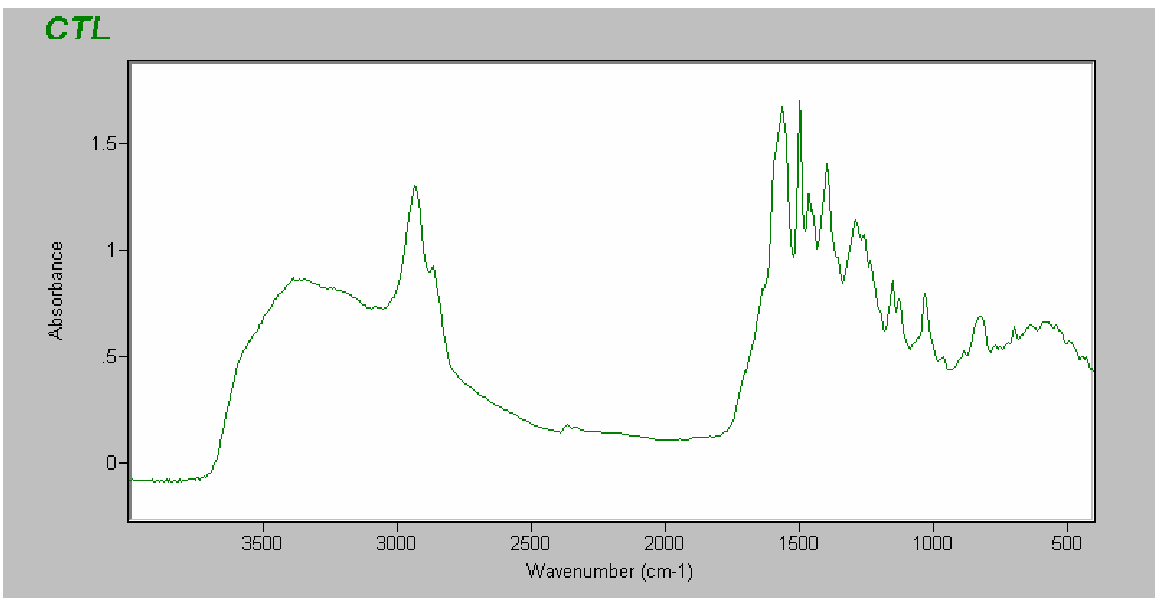
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE EV

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.49
Density	1.045
% Solids	13.78

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

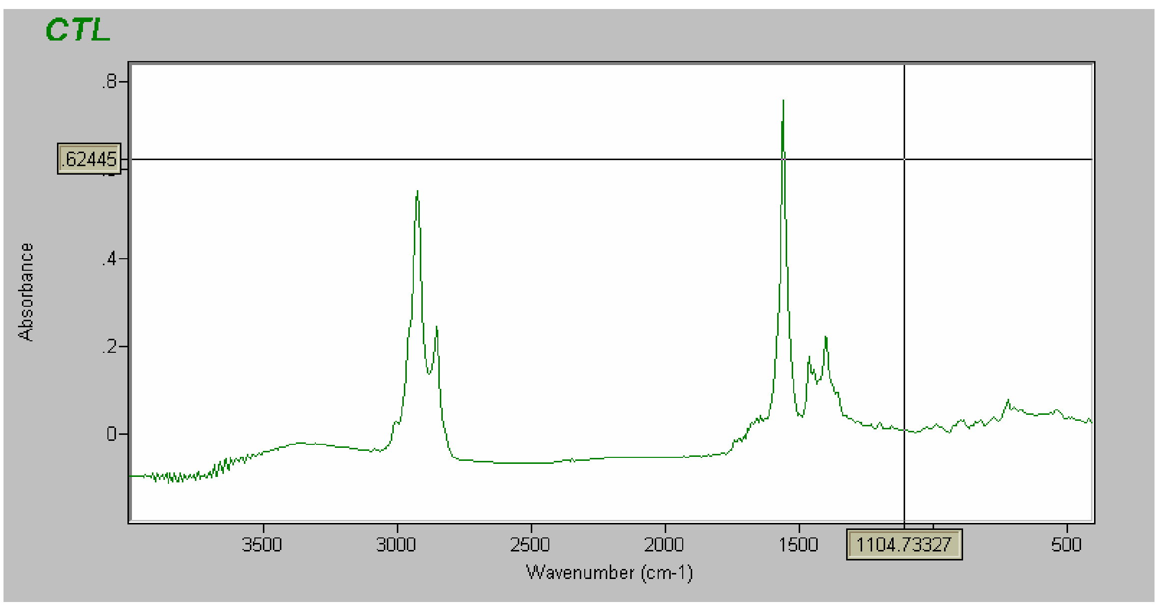
ADMIXTURE NO. 320240ZZ

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	9.98
Density	1.010
% Solids	8.93

The infrared spectrum is consistent with an air entraining admixture containing rosin soap.



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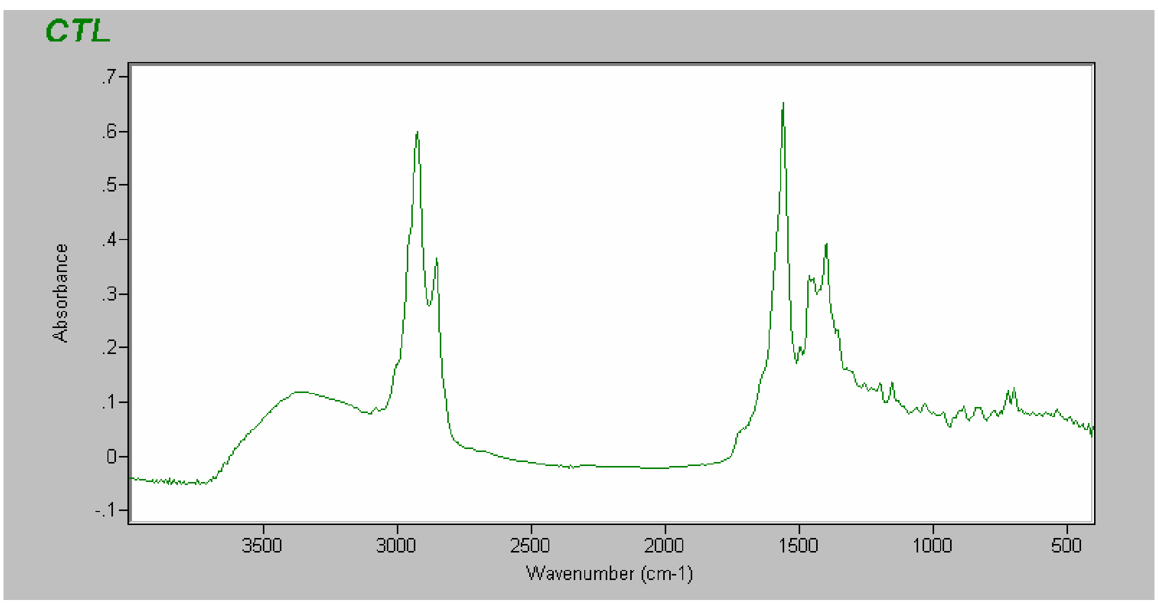
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240BB

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.59
Density	1.040
% Solids	18.72

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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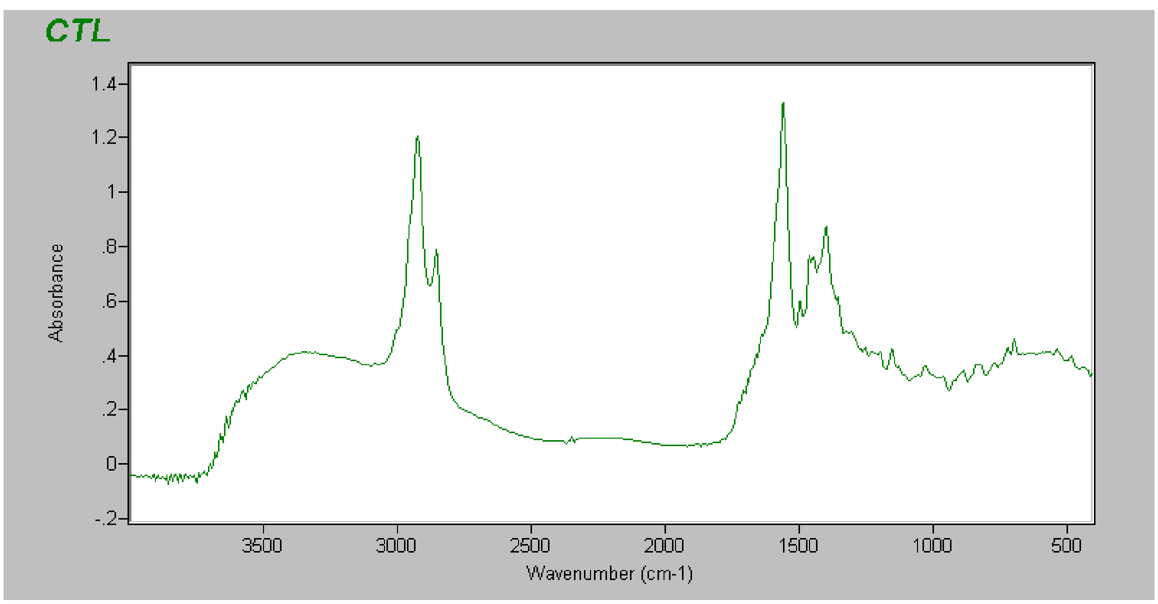
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240UU

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.86
Density	X.XX
% Solids	20.15

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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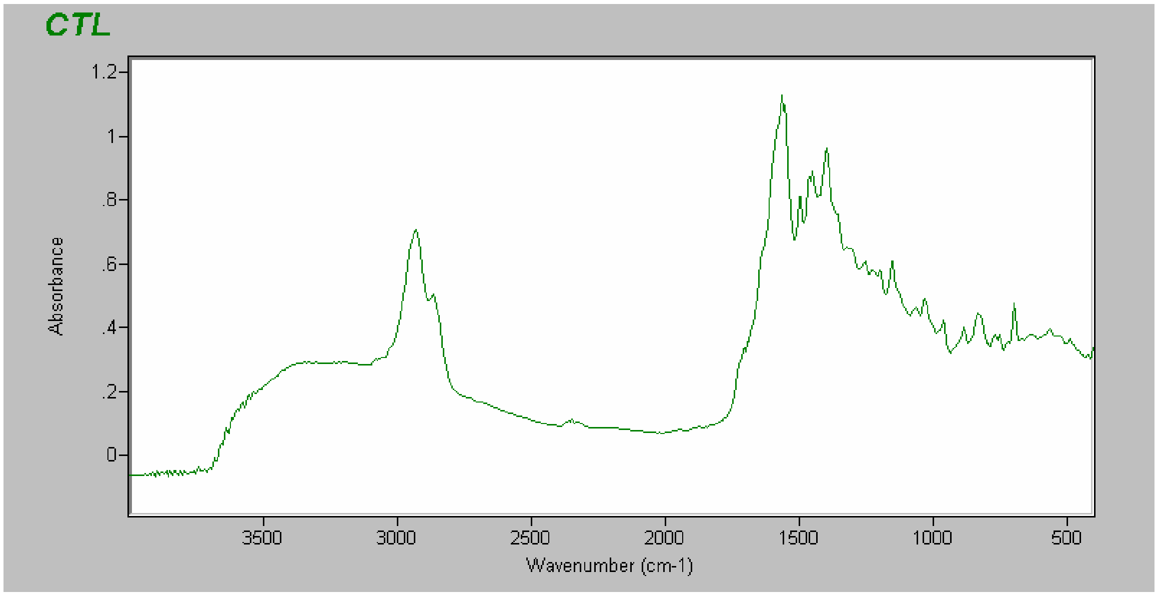
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240YY

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.7
Density	1.050
% Solids	17.49

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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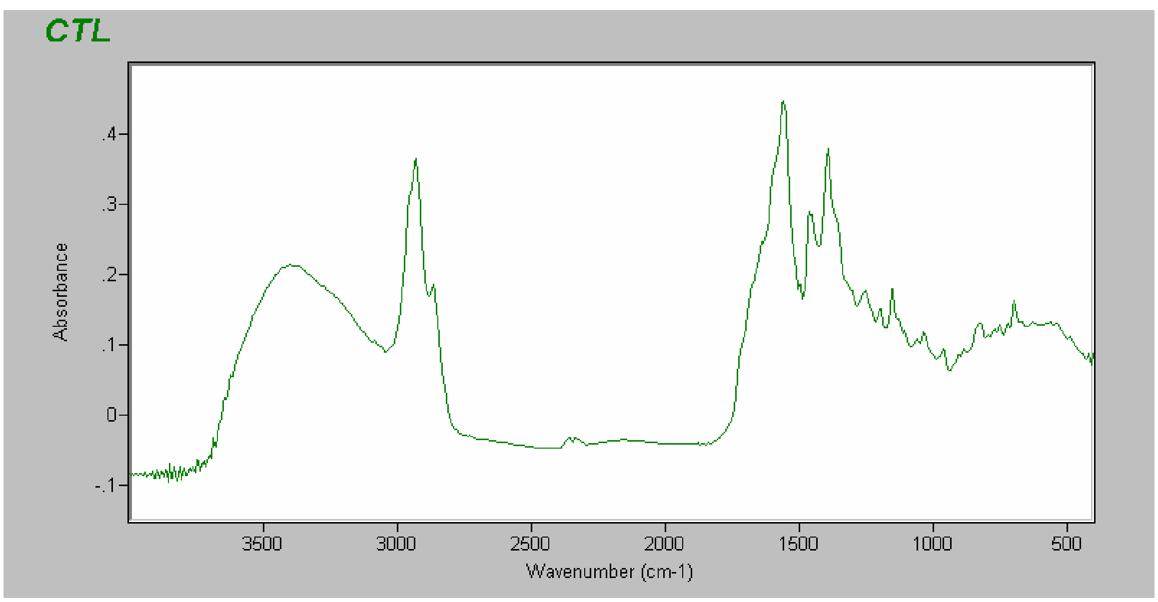
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240CCC

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	9.75
Density	1.030
% Solids	10.40

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin.



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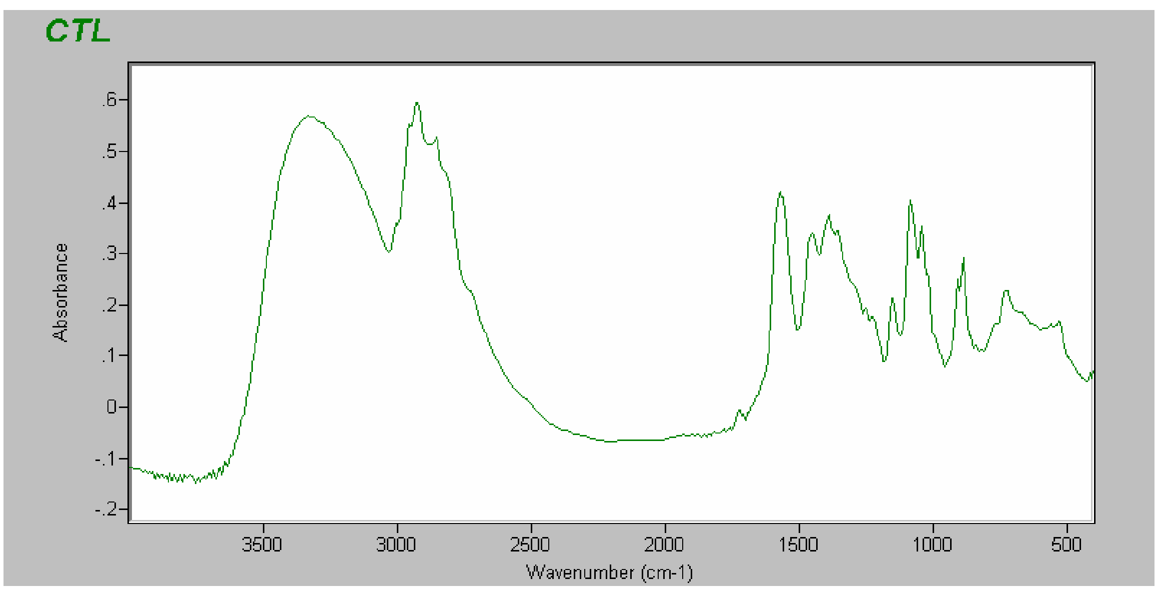
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240HH

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	10.77
Density	1.030
% Solids	20.59

The infrared spectrum is consistent with an air entraining admixture containing vinsol resin and fatty acids.



FOAM DRAINAGE DATA OF THE SELECTED ADMIXTURES

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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

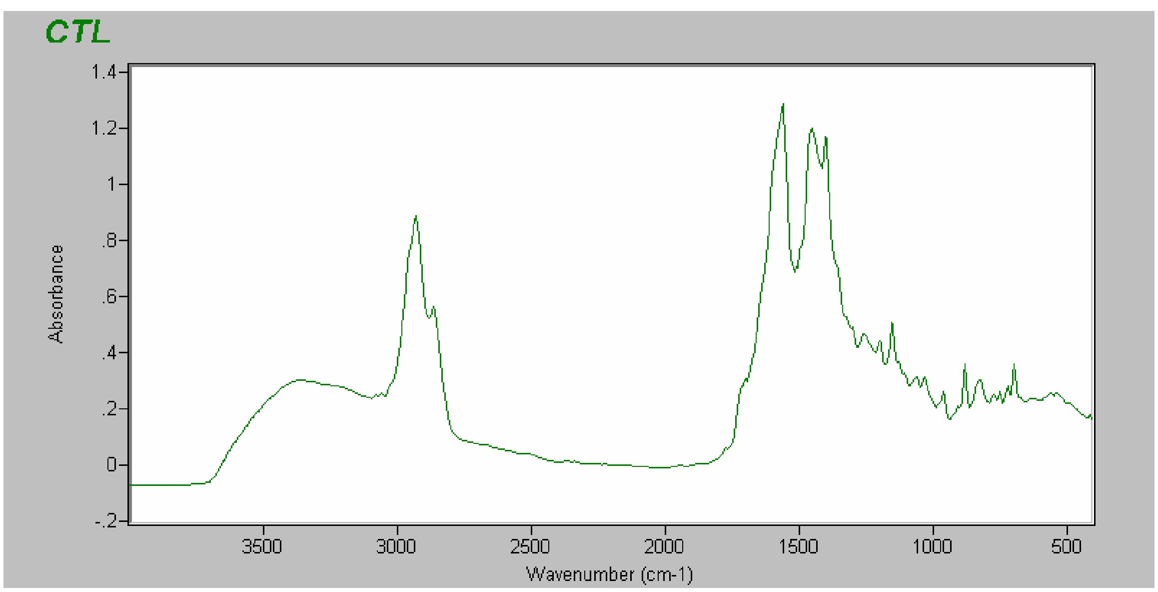
ADMIXTURE NO. 320240Q

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.2
Density	1.050
% Solids	16.2

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin.



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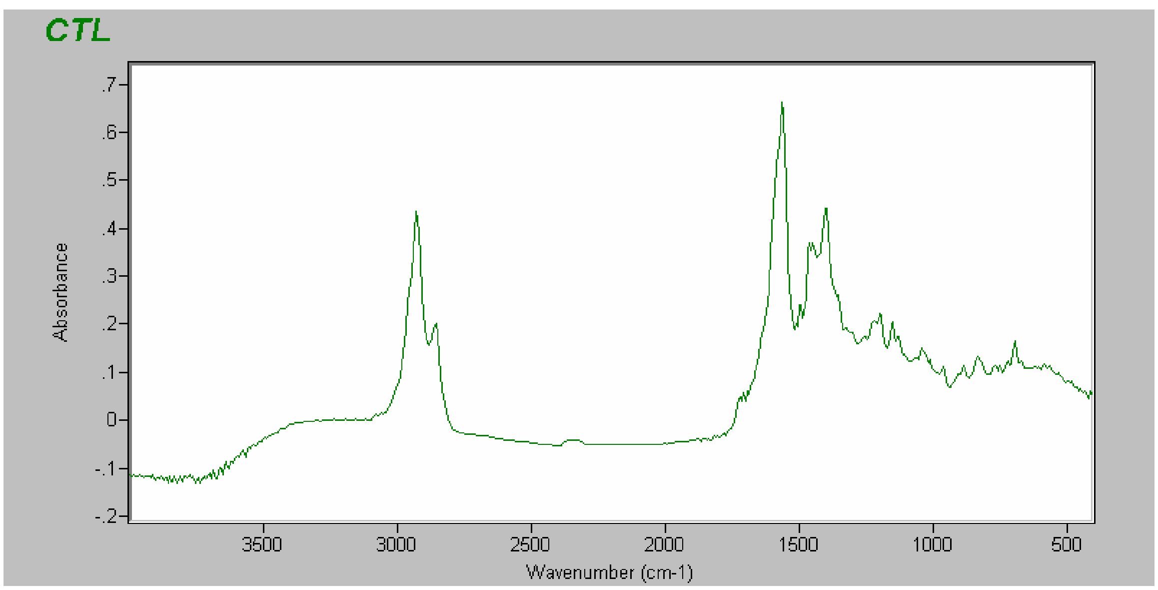
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240II

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	12.34
Density	1.030
% Solids	13.51

The infrared spectrum is consistent with an air entraining admixture containing neutralized vinsol resin and rosin.



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NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

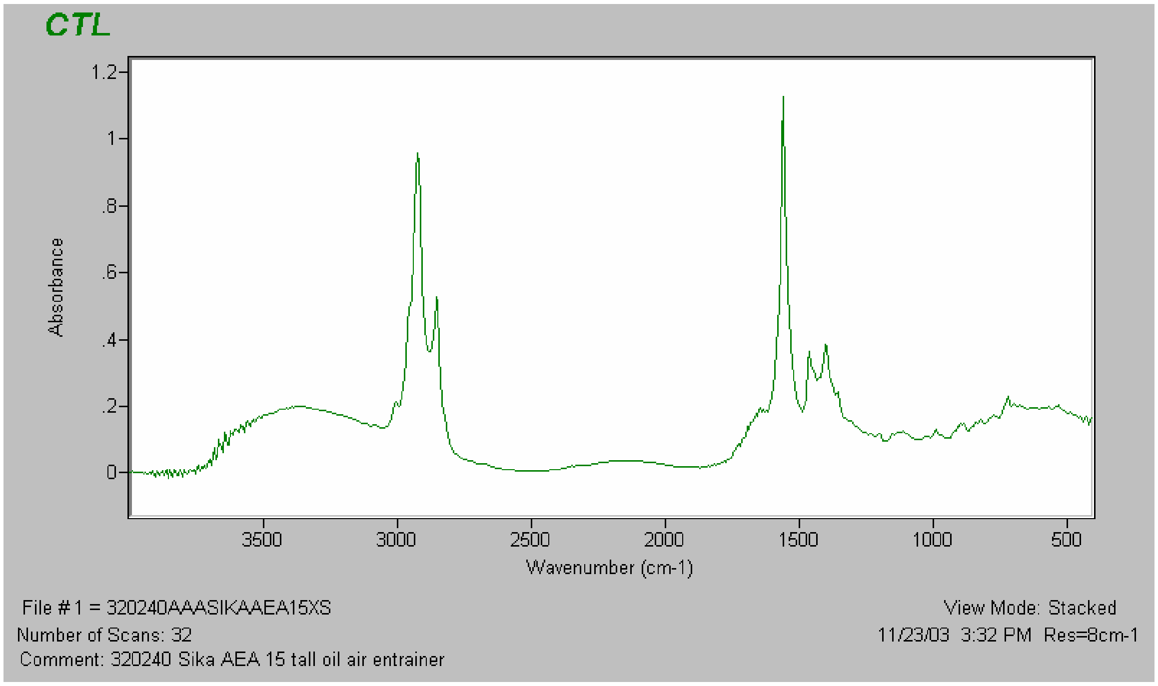
ADMIXTURE NO. 320240AAA

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.41
Density	1.045
% Solids	16.12

The infrared spectrum is consistent with an air entraining admixture containing rosin soap.



National Cooperative Highway Research Program
NCHRP 18-10
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BASELINE ADMIXTURE ANALYSIS RESULTS FOR:

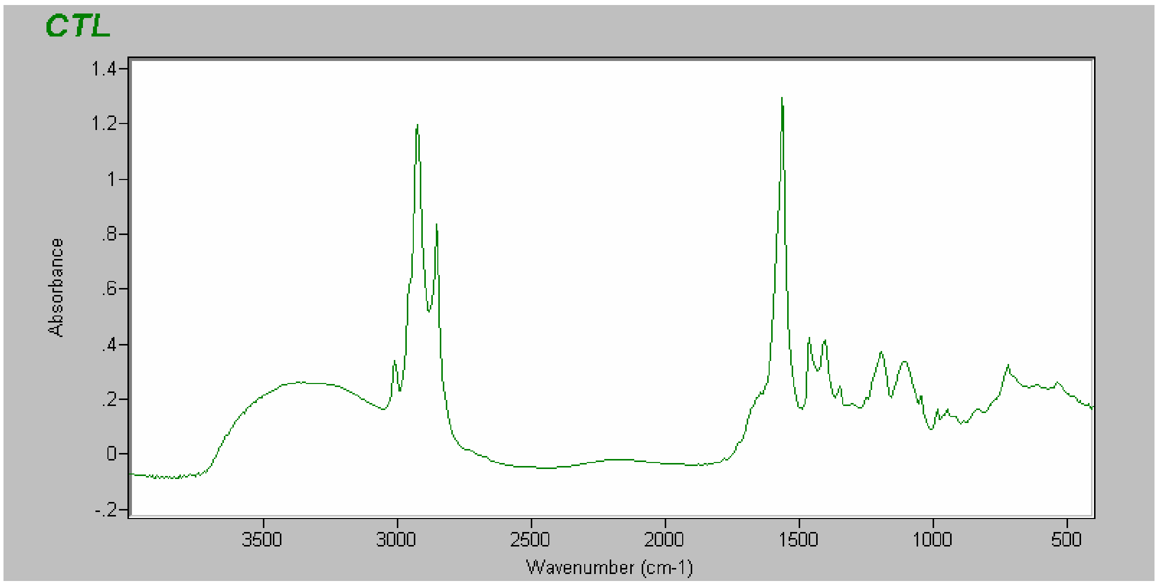
ADMIXTURE NO. 320240RR

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	11.06
Density	1.015
% Solids	12.51

The infrared spectrum is consistent with an air entraining admixture containing fatty acids alpha olefin sulfonate and propylene glycol.



National Cooperative Highway Research Program
NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

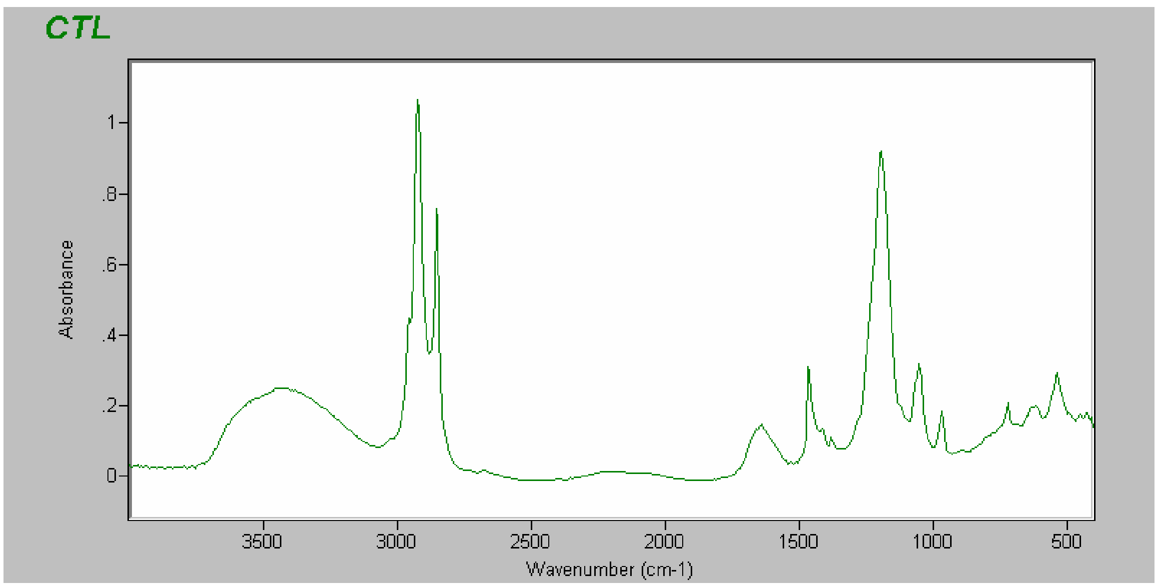
BASELINE ADMIXTURE ANALYSIS RESULTS FOR: ADMIXTURE NO. 320240C

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.61
Density	1.015
% Solids	9.46

The infrared spectrum is consistent with an air entraining admixture containing surfactant and alkyl olefin sulfonate.



National Cooperative Highway Research Program
NCHRP 18-10
Procedures for Evaluating Air-Entraining Admixtures for Highway Concrete (Phase II-Task 5a)

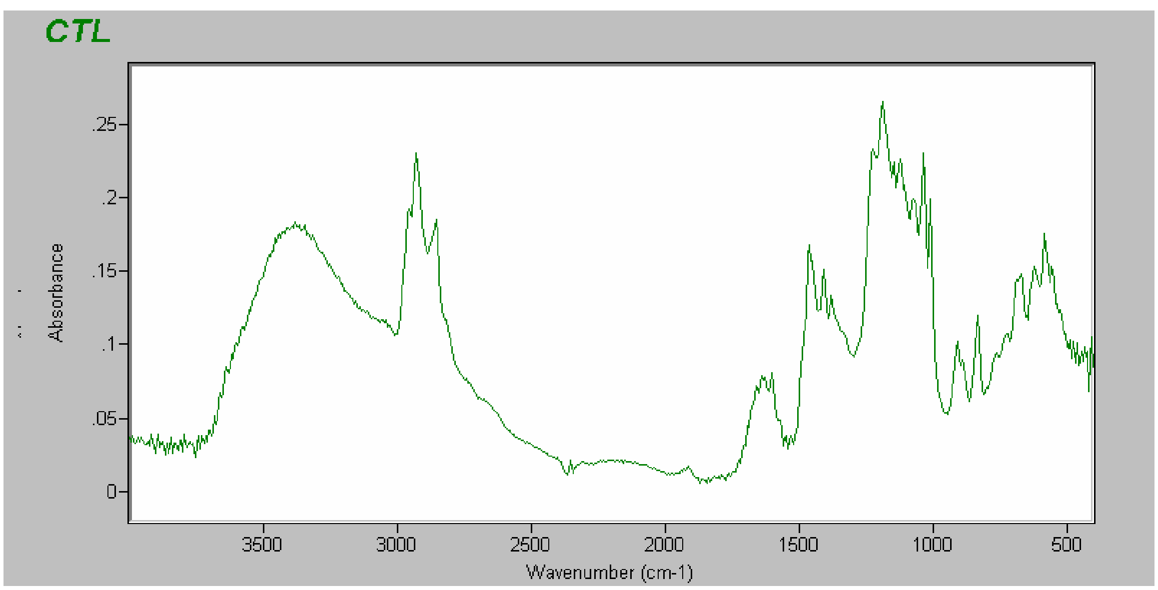
BASELINE ADMIXTURE ANALYSIS RESULTS FOR:
ADMIXTURE NO. 320240F

CTL Project No. 320240

Testing of the admixture was performed following CTL procedures.

Test	Result
pH	7.92
Density	1.015
% Solids	3.67

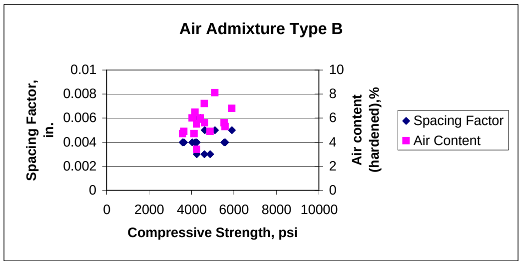
The infrared spectrum is consistent with an air entraining admixture containing benzyl sulfonate salt.



APPENDIX C

Mix No.	Mix ID	Mix Duration	Temp	Aggregate Shape	Water-Cement Ratio	Cement Alkalinity		Date Made	Mix ID	Admixture Dosage, ml	Ambient Temp, °F	Concrete Temp, °F	Slump, in	5-min. Air, %	5-min. UW, lb/ft³	Air, %	Unit Weight, lb/ft³	Final Read Time, min	Final Air, % (Fresh)	Final UW, lb/ft³	Hardened Air: Total Air, % (Hardened)	Hardened Air: Specific Surface, (in²/in³)	Hardened Air: Spacing Factor, in	Compressive Strength, psi	Flexural Strength, psi
1	B1	Short	73°F	Crushed	High	High		8/18/2004	B1	40	73	75	3.50			6.8	144.5	25	5.9	147.3	8.1	663	0.005	5110	840
2	B2	Long	73°F	Rounded	High	High		8/19/2004	B2	12	72	75	5.75	5.6	146.1	6.0	145.3	25	5.1	147.5	4.7	893	0.006	4130	660
3	B3	Short	90°F	Rounded	High	High		10/13/2004	B3	20	90	92	4.20			6.0	144.7	30	5.5	145.5	4.9	1196	0.004	3640	670
4	B4	Long	90°F	Crushed	High	High		9/28/2004	B4	23	90	88	3.00	6	146.1	6.3	145.7	35	5.4	148.1	6	930	0.004	4030	800
5	B5	Short	73°F	Rounded	Low	High		8/16/2004	B5	82	73	77	2.25			6.4	145.7	25	5.2	147.3	5.9	683	0.006	4420	730
6	B6	Long	73°F	Crushed	Low	High		8/12/2004	B6	82	75	78	0.75	5.9	147.7	6.2	147.3	25	5.6	149.3	5.3	1108	0.004	5580	830
7	B7	Short	90°F	Crushed	Low	High		9/30/2004	B7	90	90	87	0.75			6.0	147.3	30	5.3	148.9	3.4	1397	0.004	4240	780
8	B8	Long	90°F	Rounded	Low	High		10/20/2004	B8	30	90	91	2.00	5.2	147.1	6.1	145.5	35	5.4	146.7	6.5	1037	0.004	4170	760
9	B9	Short	73°F	Rounded	High	Low		8/24/2004	B9	40	73	75	6.00			6.0	144.1	30	5.4	146.1	6	718	0.006	4420	730
10	B10	Long	73°F	Crushed	High	Low		8/25/2004	B10	23	73	75	3.25	5.0	147.5	5.7	146.1	25	5.4	148.5	5.6	1288	0.004	5540	850
11	B11	Short	90°F	Crushed	High	Low		9/27/2004	B11	125	90	88	1.75			6.0	146	25	5.7	146.9	5.5	1306	0.003	4240	730
12	B12	Long	90°F	Rounded	High	Low		10/1/2004	B12	17	90	92	3.75	4.2	145.1	6.4	141.9	30	6.4	143.1	4.7	1316	0.004	3590	620
13	B13	Short	73°F	Crushed	Low	Low		8/9/2004	B13	141	74	78	0.50			5.1	148.5	35	4.0	149.7	6.8	882	0.005	5900	790
14	B14	Long	73°F	Rounded	Low	Low		8/20/2004	B14	95	73	76	1.50	6.7		6.9	145.1	30	6.1	146.5	7.2	1157	0.003	4610	660
15	B15	Short	90°F	Rounded	Low	Low		10/7/2004	B15	150	90	92	1.00			5.5	147.1	30	5.4	148.3	5.6	905	0.005	4620	700
16	B16	Long	90°F	Crushed	Low	Low		9/22/2004	B16	155	90	92	1.00	6.1	147.3	6.8	146.5	35	6.2	147.7	4.9	1514	0.003	4880	750
17	C1	Short	73°F	Crushed	High	High		8/18/2004	C1	12	72	76	2.75			6.8	144.9	30	5.3	148.1	5.5	846	0.005	4880	780
18	C2	Long	73°F	Rounded	High	High		8/19/2004	C2	7	73	75	5.25	7.4	143.1	6.8	143.7	30	5.4	145.7	6.6	638	0.007	3390	650
19	C3	Short	90°F	Rounded	High	High		10/14/2004	C3	7	90	90	6.50			6.5	143.1	35	5.8	145.5	6.9	728	0.006	4060	640
20	C4	Long	90°F	Crushed	High	High		9/28/2004	C4	10	90	88	2.50	6.1	146.5	6.1	146.5	35	5.7	146.9	5.7	1092	0.004	4470	780
21	C5	Short	73°F	Rounded	Low	High		8/16/2004	C5	24	73	76	2.25			7.0	144.9	30	6.0	146.9	9.3	716	0.004	4300	720
22	C6	Long	73°F	Crushed	Low	High		8/16/2004	C6	24	75	78	1.00	5.5		6.0	144.9	30	5.0	147.3	7.5	1310	0.003	4320	790
23	C7	Short	90°F	Crushed	Low	High		9/30/2004	C7	40	90	88	1.00			7.1	145.3	30	6.9	145.7	6.8	1437	0.003	3370	730
24	C8	Long	90°F	Rounded	Low	High		10/20/2004	C8	8	90	92	2.00	4.2	148.7	5.2	147.5	30	4.8	149.1	6.2	588	0.007	4960	750
25	C9	Short	73°F	Rounded	High	Low		8/24/2004	C9	11	72	75	4.75			6.2	144.5	25	5.3	145.7	5.1	734	0.006	4860	750
26	C10	Long	73°F	Crushed	High	Low		8/25/2004	C10	12	73	75	3.50	6	146.5	6.4	145.7	30	5.6	148.1	6	1051	0.004	5050	790
27	C11	Short	90°F	Crushed	High	Low		9/27/2004	C11	41	90	88	2.00			6.1	145.7	25	5.5	146.9	4.9	1022	0.005	4710	790
28	C12	Long	90°F	Rounded	High	Low		10/1/2004	C12	8	90	89	3.50	4.5	146.9	5.5	145.3	35	4.6	147.3	3.3	1420	0.004	4450	660
29	C13	Short	73°F	Crushed	Low	Low		8/9/2004	C13	131	74	77	1.00			6.9	145.3	35	6.0	148.3	5.5	1108	0.004	4980	660
30	C14	Long	73°F	Rounded	Low	Low		8/23/2004	C14	17	73	77	1.50	5.4	148.1	5.9	146.9	30	5.5	148.1	5.4	1080	0.004	5110	730
31	C15	Short	90°F	Rounded	Low	Low		10/7/2004	C15	32	90	92	1.25			5.3	146.7	30	5.1	147.9	3.8	816	0.007	4730	650
32	C16	Long	90°F	Crushed	Low	Low		9/22/2009	C16	49	91	89	1.00	5.8	147.1	6.7	145.7	35	6.3	147.3	4.8	1227	0.005	4350	710
33	D1	Short	73°F	Crushed	High	High		8/18/2004	D1	22	73	76	3.00			6.4	144.9	30	5.4	147.9	7.8	700	0.005	5080	800
34	D2	Long	73°F	Rounded	High	High		8/19/2004	D2	10	73	76	5.25	5.4		5.4	145.3	30	4.6	146.7	4.8	758	0.006	4700	660
35	D3	Short	90°F	Rounded	High	High		10/14/2004	D3	15	90	91	5.50			6.5	143.9	35	5.5	145.9	6	660	0.007	4310	650
36	D4	Long	90°F	Crushed	High	High		9/28/2004	D4	23	90	89	2.75	6	146.1	6.4	145.7	35	5.8	146.5	5.6	1057	0.005	4160	750
37	D5	Short	73°F	Rounded	Low	High		8/16/2004	D5	29	73	76	1.50			5.1	147.7	45	4.1	150.1	5.4	684	0.007	5090	750
38	D6	Long	73°F	Crushed	Low	High		8/16/2004	D6	29	75	78	1.00			6.0	147.3	30	5.0	150.1	4.3	865	0.006	5440	930
39	D7	Short	90°F	Crushed	Low	High		9/30/2004	D7	105	90	88	1.00			6.6	146.1	30		148.5	5.1	1181	0.004	4310	790
40	D8	Long	90°F	Rounded	Low	High		10/20/2004	D8	18	90	92	2.00	3.9	149.1	5.0	147.9	30	4.5	149.1	4.4	632	0.008	4700	760
41	D9	Short	73°F	Rounded	High	Low		8/24/2004	D9	23	73	75	5.50			5.9	144.5	35	4.8	147.3	6.7	652	0.005	5020	760
42	D10	Long	73°F	Crushed	High	Low		8/25/2004	D10	27	73	76	3.25	6.1	146.9	6.9	144.5	30	6.3	146.9	7	1082	0.004	4480	740
43	D11	Short	90°F	Crushed	High	Low		9/27/2004	D11	100	91	88	2.00			5.5	146.9	20	4.8	148.5	3.6	1131	0.005	4740	730
44	D12	Long	90°F	Rounded	High	Low		10/25/2004	D12	20	90	89	2.00	5.6	145.5	6.4	144.3	30	5.7	145.9	6.4	829	0.005	4420	640
45	D13	Short	73°F	Crushed	Low	Low		8/9/2004	D13	125	74	77	0.75			5.2	148.9	35	4.0	150.7	5.1	812	0.006	5390	710
46	D14	Long	73°F	Rounded	Low	Low		8/23/2004	D14	68	75	78	1.25	6	146.5	6.6	145.3	25	5.6	148.9	4.8	1128	0.005	5140	730
47	D15	Short	90°F	Rounded	Low	Low		10/7/2004	D15	70	90	89	1.10			5.6	146.7	30	4.5	149.1	3.7	866	0.006	4360	620
48	D16	Long	90°F	Crushed	Low	Low		9/2/2004	D16	80	91	90	1.00	4.8	148.5	6.9	145.7	30	6.4	146.9	4.9	2126	0.002	4880	760
49	E1	Short	73°F	Crushed	High	High		8/18/2004	E1	19	72	75	3.75			7.0	144.9	30	5.7	148.9	6.3	781	0.004	4530	740
50	E2	Long	73°F	Rounded	High	High		8/20/2004	E2	9	73	76	5.25	6.9	143.7	6.1	145.5	30	5.1	147.5	7.6	1004	0.003	4150	710
51	E3	Short	90°F	Rounded	High	High		10/14/2004	E3	12	90	92	5.50			6.6	143.1	35	5.3	145.9	5.3	784	0.006	4090	640
52	E4	Long	90°F	Crushed	High	High		9/29/2004	E4	23	91	89	2.00	7.4	144.1	6.0	146.5	35	5.0	148.5	4.1	1144	0.005	3790	710
53	E5	Short	73°F	Rounded	Low	High		8/17/2004	E5	32	73	76	2.00			6.8	144.9	30	5.1	148.9	5.9	767	0.006	4410	680
54	E6	Long	73°F	Crushed	Low	High		8/17/2004	E6	130	73	77	7.10	143.3							6.9	1103	0.004	4530	740
55	E7	Short	90°F	Crushed	Low	High		9/30/2004	E7	99	91	89	0.75			5.9	147.3	30	4.8	149.7	4.2	1445	0.004	4280	750
56	E8	Long	90°F	Rounded	Low	High		10/21/2004	E8	25	90	92	1.80	4.8	149.1	5.4	147.1	30	5.0	148.3	3.6	811	0.007	4990	790
57	E9	Short	73°F	Rounded	High	Low		8/24/2004	E9	19	73	76	5.25			6.8	144.5	25	5.3	146.9	6.4	690	0.006	4910	750
58	E10	Long	73°F	Crushed	High	Low		8/25/2004	E10	23	73	75	3.00	6	147.5	6.8	145.3	20	5.7	146.5	4.4	1382	0.004	5180	740

Mix No.	Mix ID	Mix Duration	Temp	Aggregate Shape	Water-Cement Ratio	Cement Alkalinity		Date Made	Mix ID	Admixture Dosage, ml	Ambient Temp, °F	Concrete Temp, °F	Slump, in	5-min. Air, %	5-min. UW, lb/ft^3	Air, %	Unit Weight, lb/ft^3	Final Read Time, min	Final Air, % (Fresh)	Final UW, lb/ft^3	Total Air, % (Hardened)	Specific Surface, (in^2/in^3)	Spacing Factor, in	Compressive Strength, psi	Flexural Strength, psi
59	E11	Short	90°F	Crushed	High	Low		9/24/2004	E11	92	92	90	2.75			6.8	145.3	35	5.3	148.1	5.8	1074	0.004	4520	690
60	E12	Long	90°F	Rounded	High	Low		10/25/2004	E12	13	90	92	3.40	4.7	146.3	5.4	145.5	25	5.0	146.3	5.6	920	0.005	4550	610
61	E13	Short	73°F	Crushed	Low	Low		8/11/2004	E13	131	73	76	1.25			7.3	145.3				4.1	737	0.007	5720	780
62	E14	Long	73°F	Rounded	Low	Low		8/24/2004	E14	35	73	75	2.00	6.2	147.3	6.9	145.3	30	6.3	146.5	5	1492	0.003	4590	710
63	E15	Short	90°F	Rounded	Low	Low		10/8/2004	E15	48	90	90	1.50			5.3	146.7	30	4.7	148.7	5.8	939	0.005	4580	720
64	E16	Long	90°F	Crushed	Low	Low		9/22/2004	E16	43	91	86	1.00	5	148.5	6.1	146.9	30	5.4	148.5	5.6	1342	0.004	4480	710
65	M1	Short	73°F	Crushed	High	High		8/19/2004	M1	23	72	74	3.25			6.7	145.7	30	6.0	146.7	6.5	1111	0.004	4330	720
66	M2	Long	73°F	Rounded	High	High		8/19/2004	M2	11	74	77	5.00	7.1		6.9	143.7	30	6.2	144.9	7.7	813	0.004	3750	650
67	M3	Short	90°F	Rounded	High	High		10/15/2004	M3	10	90	92	3.80			6.2	143.1	35	6.0	145.1	7	823	0.005	3710	560
68	M4	Long	90°F	Crushed	High	High		9/29/2004	M4	16	90	90	2.25	6.1	146.5	6.3	146.1	30	6.0	146.9	5.9	1541	0.003	3670	750
69	M5	Short	73°F	Rounded	Low	High		8/16/2004	M5	74	73	76	2.00			5.9	146.1	25	4.8	148.1	4.2	937	0.006	4060	740
70	M6	Long	73°F	Crushed	Low	High		8/12/2004	M6	92	73	77	1.00	6.5		7.0	145.7	30	6.2	144.9	5.8	1326	0.004	4830	680
71	M7	Short	90°F	Crushed	Low	High		9/29/2004	M7	99	90	90	0.75			6.3	147.3	40	5.2	150.1	4	1479	0.004	3950	750
72	M8	Long	90°F	Rounded	Low	High		10/21/2004	M8	50	90	92	1.60	6	146.3	7.2	144.7	40	6.8	145.1	4	1297	0.004	3910	670
73	M9	Short	73°F	Rounded	High	Low		8/24/2004	M9	25	73	76	5.00			6.2	144.5	30	5.2	145.9	6.6	1029	0.004	4050	680
74	M10	Long	73°F	Crushed	High	Low		8/26/2004	M10	26	72	76	3.00	6	146.5	6.7	145.3	35	6.1	146.9	5.2	1809	0.003	4680	740
75	M11	Short	90°F	Crushed	High	Low		9/22/2004	M11	105	90	88	2.00			6.2	145.7	30	5.4	147.3	3.9	1170	0.005	4230	710
76	M12	Long	90°F	Rounded	High	Low		10/25/2004	M12	15	90	90	4.20	6	144.7	6.4	143.9	30	5.9	145.5	5.4	1042	0.004	3760	640
77	M13	Short	73°F	Crushed	Low	Low		8/9/2004	M13	136	75	78	0.75			5.1	148.5	35	4.0	149.7	5.3	1394	0.003	5210	730
78	M14	Long	73°F	Rounded	Low	Low		8/23/2004	M14	45	73	76	1.50	5	148.1	6.8	145.3	30	5.7	147.5	7.5	1623	0.002	4190	660
79	M15	Short	90°F	Rounded	Low	Low		10/8/2004	M15	62	90	89	1.25			6.0	145.9	30	5.4	147.5	3.8	1287	0.004	3890	580
80	M16	Long	90°F	Crushed	Low	Low		8/30/2004	M16	146	90	92	0.50	5+30ml	149.3	6.8	147.3	35	5.7	148.9	4.1	1750	0.003	5430	700
81	S1	Short	73°F	Crushed	High	High		8/19/2004	S1	11	72	75	3.25			6.4	145.7	40	5.4	148.1	5.1	1055	0.005	4550	790
82	S2	Long	73°F	Rounded	High	High		8/20/2004	S2	6	73	75	5.50	6.1	145.3	7.1	143.3	30	5.9	146.5	7.2	686	0.006	3760	660
83	S3	Short	90°F	Rounded	High	High		10/19/2004	S3	8	90	92	4.00			5.5	145.1	30	4.9	147.5	4.7	740	0.007	3980	640
84	S4	Long	90°F	Crushed	High	High		9/29/2004	S4	8	90	88	2.00	5.7	147.3	6.0	146.1	30	5.0	148.9	5	1112	0.005	4000	700
85	S5	Short	73°F	Rounded	Low	High		8/17/2004	S5	30	73	76	1.75			5.5	148.5	30	4.5	149.7	4.5	882	0.006	4540	710
86	S6	Long	73°F	Crushed	Low	High		8/17/2004	S6	35	74	78	1.00	5.5	148.9	6.8	146.5	30	5.8	148.3	7.6	1300	0.003	4760	730
87	S7	Short	90°F	Crushed	Low	High		9/29/2004	S7	105	89	87	0.75			5.8	148.1	25	5.3	149.7	4.2	1357	0.004	4480	830
88	S8	Long	90°F	Rounded	Low	High		10/21/2004	S8	15	90	91	2.00	5.2	147.1	6.8	145.5	30	5.8	146.3	4.6	1106	0.005	4290	730
89	S9	Short	73°F	Rounded	High	Low		8/24/2004	S9	15	73	75	4.00			5.6	145.9	35	4.6	148.3	5.6	868	0.005	4150	720
90	S10	Long	73°F	Crushed	High	Low		8/26/2004	S10	16	73	76	2.75	4.6+10ml	148.1	6.4	145.3	30	5.7	146.9	3.6	1504	0.004	4810	790
91	S11	Short	90°F	Crushed	High	Low		9/23/2004	S11	65	91	88	1.75			6.3	146.5	30	5.7	146.3	5.3	1507	0.003	4540	740
92	S12	Long	90°F	Rounded	High	Low		9/25/2004	S12	8	90	90	4.40	5.5	145.1	6.7	143.1	30	5.9	145.1	6.6	1044	0.004	4330	620
93	S13	Short	73°F	Crushed	Low	Low		8/11/2004	S13	196	72	75	1.00			5.0	149.7	30			4.6	1036	0.005	5860	750
94	S14	Long	73°F	Rounded	Low	Low		8/24/2004	S14	24	73	75	1.50			6.0	146.5	25	5.2	148.3	4.2	1547	0.003	4260	740
95	S15	Short	90°F	Rounded	Low	Low		10/13/2004	S15	120	90	92	1.30			5.0	146.7	30	4.5	148.7	5.5	662	0.007	3720	580
96	S16	Long	90°F	Crushed	Low	Low		9/23/2004	S16	70	90	88	0.75	5	148.9	6.5	146.9	30	6.0	148.1	5	1175	0.004	4520	770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Air content (hardened),%
Compressive Strength, psi
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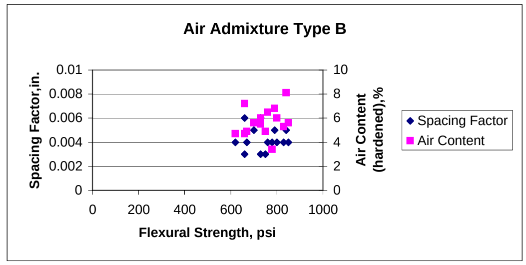
Spacing Factor
Air Content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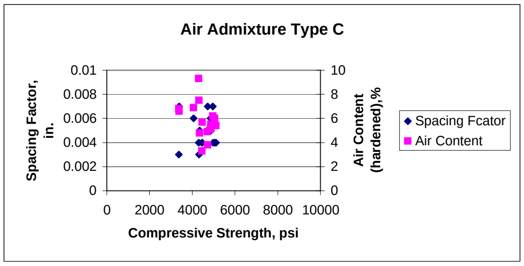
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Spacing Fcator
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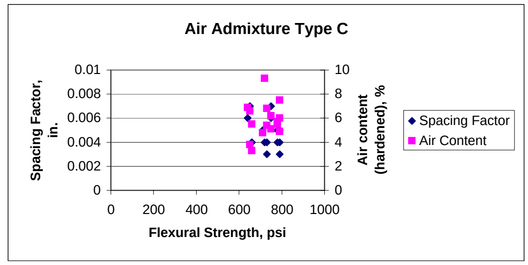
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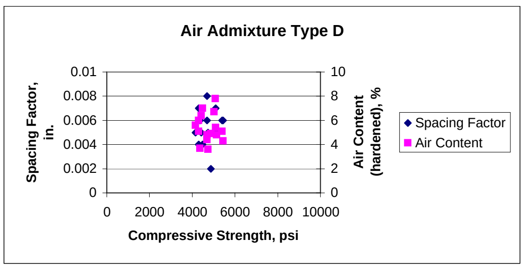
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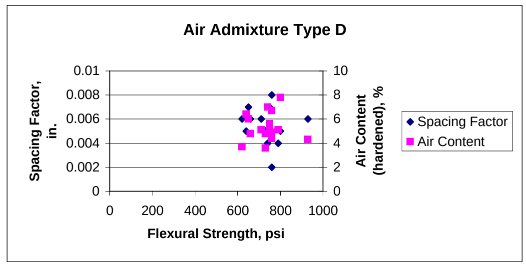
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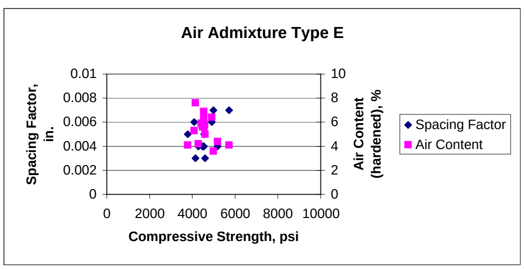
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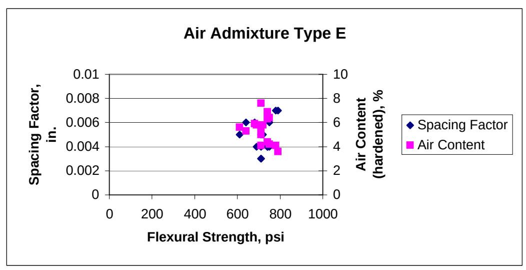
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Spacing Factor
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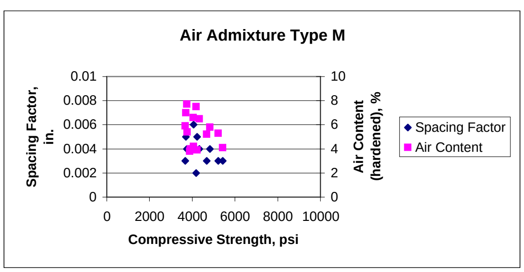
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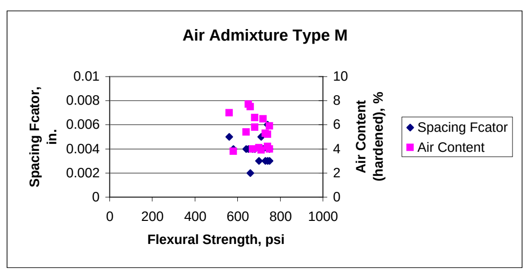
Spacing Factor
Air Content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Spacing Fcator, in.
Air Content (hardened), %
Flexural Strength, psi
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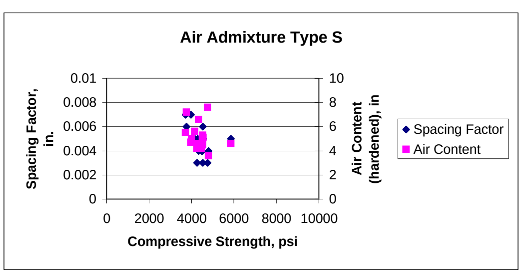
Spacing Fcator
Air Content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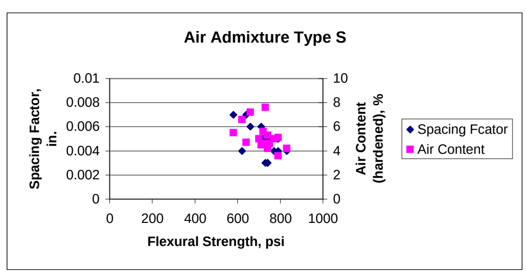
Spacing Factor
Air Content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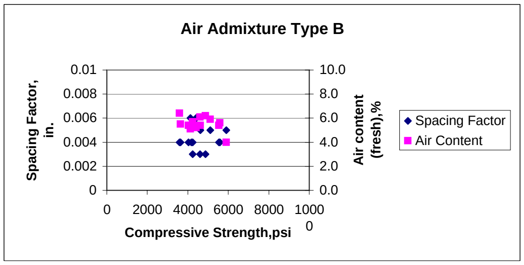
Air Content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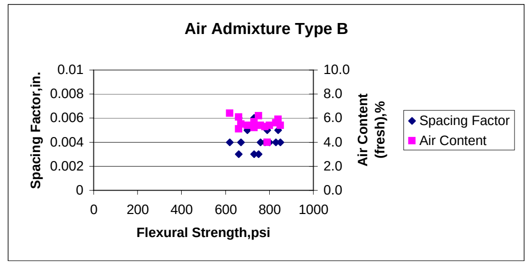
Compressive Strength,psi
Spacing Factor
Air Content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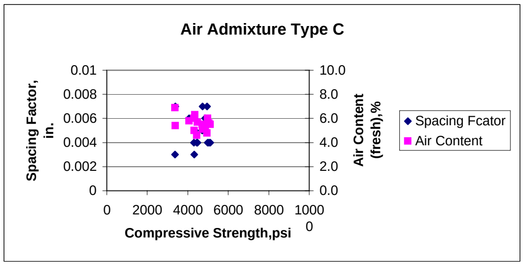
Air Content (fresh),%
Flexural Strength,psi
Spacing Factor
Air Content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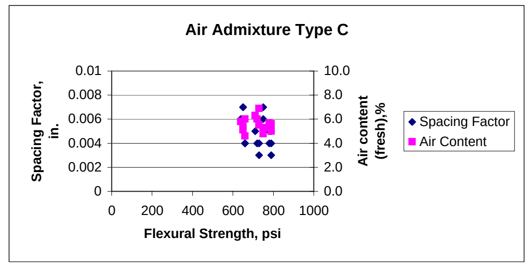
Air Content (fresh),%
Compressive Strength,psi
Spacing Fcator
Air Content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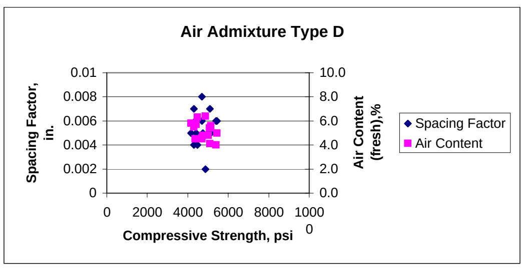
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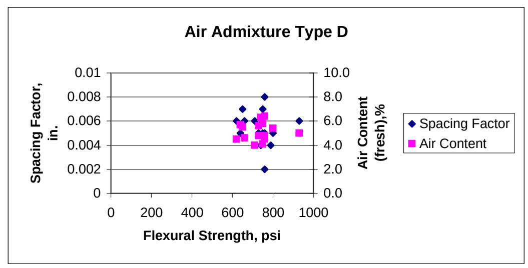
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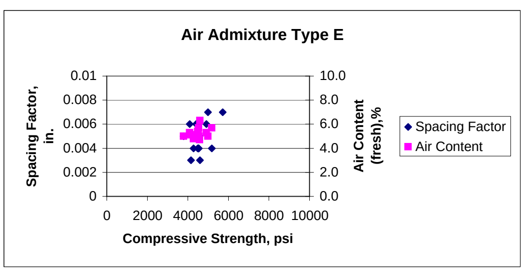
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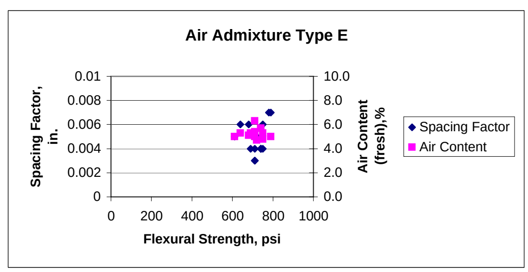
Compressive Strength, psi
Spacing Factor
Air Content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Spacing Factor, in.
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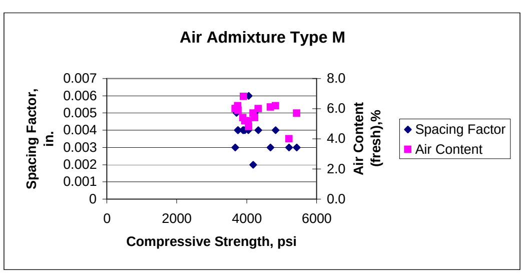
Flexural Strength, psi
Spacing Factor
Air Content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Spacing Factor, in.
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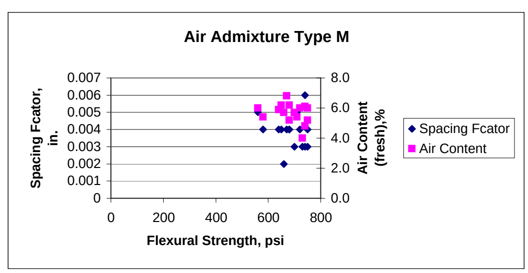
Compressive Strength, psi
Spacing Factor
Air Content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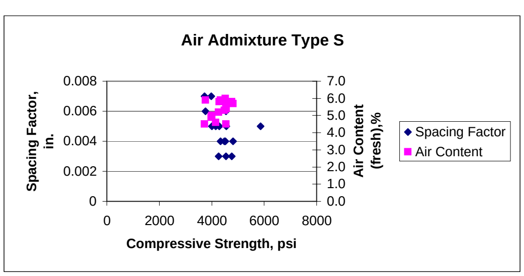
Flexural Strength, psi
Spacing Fcator
Air Content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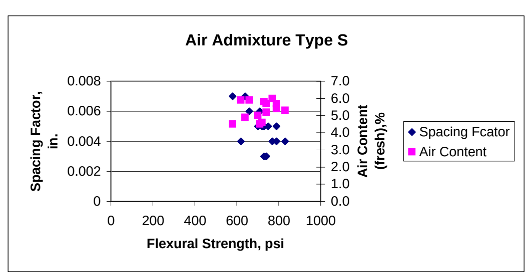
Spacing Factor
Air Content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Flexural Strength, psi
Spacing Fcator
Air Content