Reuse of Solidified Steel Industry Sludge Waste for Transportation Facilities

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There is much interest in the industry in finding safe, reliable, and economic ways to detoxify and dispose of production wastes. A laboratory test program was designed to study the feasibility of reuse of solidified steel industry waste sludges as a construction material. The particular application reported is the use of the material as a capping barrier system over an existing lagoon. Random cracking of the solidified slabs is investigated. Various strength tests on cured specimens of wet mixed and solidified samples were conducted. The specimens were cured in seven different environments of temperature and humidity. The laboratory tests included unconfined compression, unconfined tension, and fracture toughness tests. The strength parameters were correlated with curing time, curing temperature, mix water content, and proportion of surface active reagents added. It was observed that the curing conditions that brought about higher compressive strengths were not favorable for the development of fracture resistance of the material. The unconfined compressive and tensile strengths of the material appeared to gain high values when the material was cured in high humidity–moderate temperature environments, whereas its fracture resistance improved at low moisture gradients. The high and low humidity conditions resulted in poor fracture resistance. The results obtained with varying contents of the surface active reagents indicated that there may be optimum proportions of these additives for which the highest strength and fracture resistance values are developed. Increasing the mix water content appeared to reduce both the strength and fracture resistance of the material.

The subject of resource recovery and reuse of waste materials has gained much attention within the past decade, principally because of the increased number of environmental statutes and regulations that necessitate minimizing waste disposal (*1,2*). The benefits of reusing stabilized or solidified waste materials should be twofold: (a) compliance with regulations, thus helping to reduce environmental hazard, and (b) added economy. These materials can be an inexpensive alternative for conventional materials provided that (a) there are no adverse effects to the environment, and (b) the performance of the created material is similar or equal to the one it replaces.

With the landbans of the Environmental Protection Agency (EPA) (*3*), the chemical fixation and solidification (CFS) of liquid and sludge wastes vastly increased. The use of CFS for waste materials dates back to the 1970s (*4*). However, the development and use of the technology in ground improvement methods (e.g., soil stabilization, rock and soil grouting) and in construction of base courses for paved surfaces have been around since long before the 1970s (*5*). Historically, the types of materials used as stabilizing agents have ranged from earthen (lime, gypsum) and silicious (cement, fly ash) materials, to various resins and other polymerizing agents. ASTM and AASHTO have developed standards for mixing and testing stabilized systems for construction of earth structures. A set of standards has not been developed for mixing and testing stabilized and or solidified products of waste materials. However, the need for considerable work in this area has been recognized and standards are emerging. It is obviously more difficult to standardize the application of CFS technology for waste materials because of the many types of waste products. Such variation of the chemistry dictates that each process be compatible with the specific waste constituents. Therefore each process must be developed independently to optimize the values of a selected number of physical and chemical properties of the end product. Selection of those properties to optimize—such as permeability, leachability, strength, rigidity, and durability—should depend on the intended function of the end product.

A study was undertaken to investigate the feasibility of using a solidified steel industry sludge as a construction material for earthen structures. The results presented pertain to the study of possible causes of random cracking and spalling of the concrete-like end product when used as an interim cover material on an existing dewatered sludge lagoon. Both the field data and the laboratory test results appear to confirm the assessment that the strength development and the fracture resistance of the material are sensitive to variations in the design mixture and to curing conditions and temperature.

BACKGROUND

Definitions

The terms "stabilization," "solidification," and "chemical fixation" of waste materials have been used interchangeably. EPA's definition of these terms has been reported in a number of publications (*6,7*). Stabilization or chemical fixation of a waste is the chemical modification of the material to detoxify its hazardous constituents or significantly reduce its leachability. This modification may not necessarily improve the physical properties of the material. Solidification refers to encapsulation of the waste in a solid matrix with high structural integrity. The waste matter is isolated in an impervious capsule that does not allow its migration.

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Products of waste materials, especially those considered for reuse, should possess the following requirements: (a) minimized solubility and mobility (leachability) of toxic substances, (b) minimized permeability and thus leachability and volume change, (c) physical stability, strength, and durability. In the United States, compliance to the first requirement, namely minimized solubility and leachability, is assessed by the EPA Extraction Procedure Toxicity (EPT) or the Toxicity Characteristic Leaching Procedure (TCLP) test. The physical properties that are often used as indicators of minimized leachability and physical integrity are hydraulic conductivity (permeability), unconfined compressive strength, bulk density, specific gravity, and freeze-thaw and wet-dry durability. General guidelines determined by EPA suggest an unconfined compressive strength value of 50 psi and a coefficient of permeability value of 10^{-7} cm/sec. However, a large range of unconfined compressive strengths and permeabilities are achieved by various solidification techniques. These values have been reported to range from 11 to 3,000 psi for strength, and from 10^{-4} to 10^{-8} cm/sec for permeability (*8*). Strength, permeability, and durability values obtained for solidification processes often depend on a number of factors: waste type, water content, and additive types and their mix ratio, curing time, and temperature. Depending on the intended function of the end product, the desired values of one or more physical properties can be attained by controlling a number of these factors.

Previous Work

A cement-based solidification process was used to treat a steel industry waste sludge bearing heavy metals, oils, and greases. The process produced a concrete-like material with good physical characteristics. A number of different products were made by varying the proportions of the ingredients of the original mixture. Specimens of these products were tested in the laboratory for strength and permeability. Unconfined compressive strength (28-day cured) values ranged from 90 to 120 psi, and permeability values varied between 10^{-6} to 10^{-7} cm/sec (*9*). TCLP and EPT tests of the stabilized product showed that the material is nontoxic and represents no threat to the environment.

One of the products was made by mixing the dewatered sludge (filter cake) with slag, cement, and water. The size of the slag added was screened from -1.25 to $+0.25$ in., and the cement selected was Type II. Table 1 lists some of the index and physical properties of the ingredients and the final mix measured in the laboratory.

In fall 1989, this product was applied as an interim cover to a dewatered sludge lagoon. It was mixed on site to a consistency that could be poured from a concrete-mix truck. The field mix incorporated small percentages of surface-active chemicals. These chemicals included a water-reducing surfactant (superplasticizer) to disperse the cement and increase the fluidity of the mixture, and an air-entraining surfactant to reduce segregation and improve the durability of the material. The existing subgrade surface was covered by polyethylene membrane prior to the pour of the mix to avoid migration of moisture into the desiccated material below. A 1-ft cover was poured in sections over approximately 4 acres in 1 month. Control and expansion joints were placed at regular intervals. A thin coating of rubberized sealer was applied over each section immediately after finishing the surface to reduce loss of curing water.

The material appeared to solidify within hours of the pour, which duplicated laboratory observations. As the project progressed toward completion, early pour sections revealed some cracking, which was remediated by grouting. The completed cover was left to undergo snow load and freeze-thaw during the subsequent winter and spring months; during this time no other appreciable load was applied. At the end of this time

TABLE 1 PHYSICAL PROPERTIES OF THE BASE MIXTURE AND ITS COMPONENTS

Properties	Filter Cake	Slag	Final Mix
Water content (% by total weight)	45	9	34
Water absorption (%)	-	7	-
Specific gravity	1.56	3.57	1.98
Bulk density (pcf)	-	-	85
Coefficient of permeability (cm/sec)	-	-	10^{-7}
Unconfined compressive strength (28 day, psi)	-	-	120
Volumetric shrinkage (%)	-	-	6
Linear shrinkage (%)	-	-	2
Weight loss upon 12 cycles of freeze-thaw (%)	-	-	10

extensive cracking and spalling was observed over parts of the cover. The earlier measurements of durability, shrinkage, and compressive strength on laboratory-prepared specimens had not indicated a high possibility of such an occurrence. In addition, the cracking and spalling appeared to be quite random both in location and severity. This randomness was so extensive that the performance of slabs poured side by side appeared to be entirely different—one deteriorated severely and the other maintained much of its integrity and concrete-like structure. However, close study of the field data suggested possible causes to be the particular weather conditions and temperature at the time of each pour and inadvertent variations in the quantity of mixing water.

Each slab or section was rated on a scale of 1 to 5 (1 for the best-performing slabs with minor cracking and 5 for the poorest-performing slabs with extensive cracking and spalling). The number of occurrences of slabs rated 2 (good) were then correlated with their slump, measured at the field, with average wind speed, average relative humidity, and average temperature reported on the days that those slabs were poured. These results are presented in Figures 1–4, which show the number of occurrences for all of the slabs, as well as slabs rated as good. There appears to be a meaningful correlation between the number of occurrences of the slabs rated as good and the factors given above. A slump value of 7.25 in., low wind speed at around 7 knots, relative humidity of 57.5 percent, and an average temperature of 17°C appeared to produce the largest number of well-performing slabs. It should be noted, however, that the slump value of 7 in. was the design slump of the mixture; therefore most of the slabs poured did attain a slump value within the vicinity of 7 in.

These findings indicate that the development of strength and resistance to fracturing may be strongly sensitive to the quantity of mix water and admixtures and to the rate of evaporation of water and thus curing conditions. An extensive experimental program was initiated to establish the sensitivity of strength and fracture resistance of this particular solidified product to quantity of mixing water, additives such as air-entrainment surfactants, water-cement ratio and curing conditions, and temperature. The goal was to better understand the cracking phenomenon in order to establish process guidelines for quality control of the final product. The increased understanding of long-term field performance of the material and of the ways to improve this performance should also help determine the feasibility of its utilization in various other reuse capacities, such as in constructing earth structures for transportation facilities.

INVESTIGATION

Experimental Program

Three types of tests were conducted: (a) unconfined compression, (b) unconfined penetration (*10*) or direct tension, and (c) fracture toughness (ASTM E399) (*11*). Unconfined compressive and tensile strengths were measured over a range of mix water contents and curing temperatures. The principal aim for these measurements was to determine any correlation between strength development and fracture resistance under similar conditions. In the absence of a well-defined measurement of fracture or cracking resistance of composite materials, the selected test method was based on linear elastic fracture mechanics (LEFM) theory. The LEFM theory has been quite successful in predicting crack propagation in metals for the past few decades. It also has been applied to predict fracture behavior in concrete and rock (*12*) and cement-based materials (*13*). More recently, use of this approach on compacted dry clay showed that the load necessary to pull apart a precracked specimen may be a useful indicator of fracture resis-

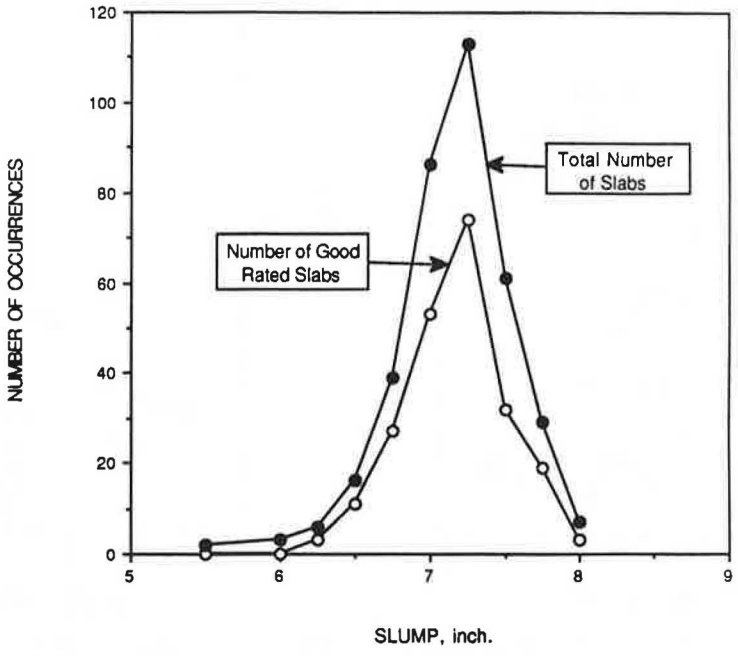

FIGURE 1 Slump versus number of slabs poured in the field.

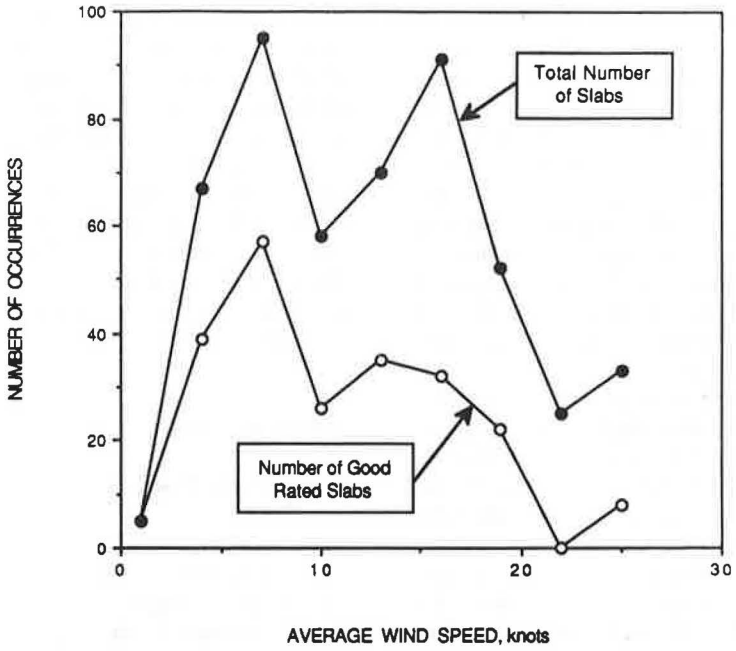

FIGURE 2 Average wind speed at the time of pour versus number of slabs in the field.

tance of solidified particulate materials. This load is called the fracture load (*11*). Details of the actual test procedure and pertinent examples can be found in a number of publications (*14,15*). The standard specimens are prepared using a mold 7.6 cm square and 0.64 cm (0.25 in.) thick. The mixture is poured and allowed to solidify in the mold. Because of the size limitation, the specimens prepared for the fracture load testing had only No. 28 mesh size slag mixed in the same proportion as that of the slag in the actual formula. Because the fracture load values were intended for use as indicators and their significance was to be evaluated with respect to each other and not alone, changing the formula in the manner described did not necessarily affect the final assessments. All of the tests were conducted on duplicate (in some cases triplicate) specimens prepared from the same batch of mix and were cured the same length of time under the same temperature and humidity conditions. The mixture would initially be in a thick slurry consistency. The strength test specimens were prepared by pouring the slurry into cylindrical (3 in. by 6 in.) waxed cardboard molds and left to set in a constant

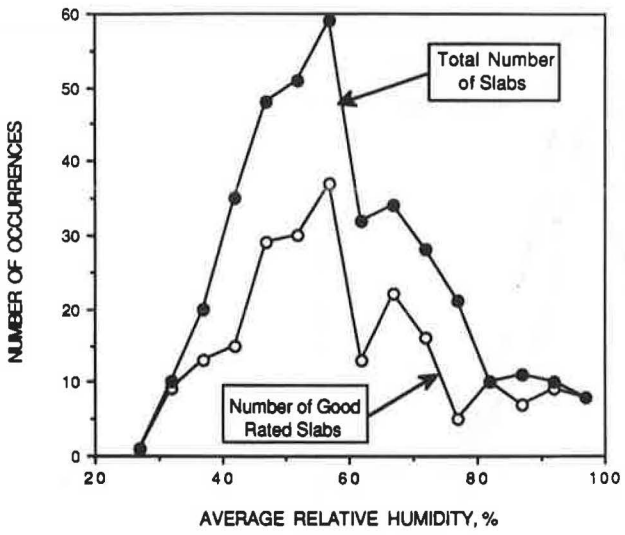

FIGURE 3 Average relative humidity at the time of the pour versus number of slabs in the field.

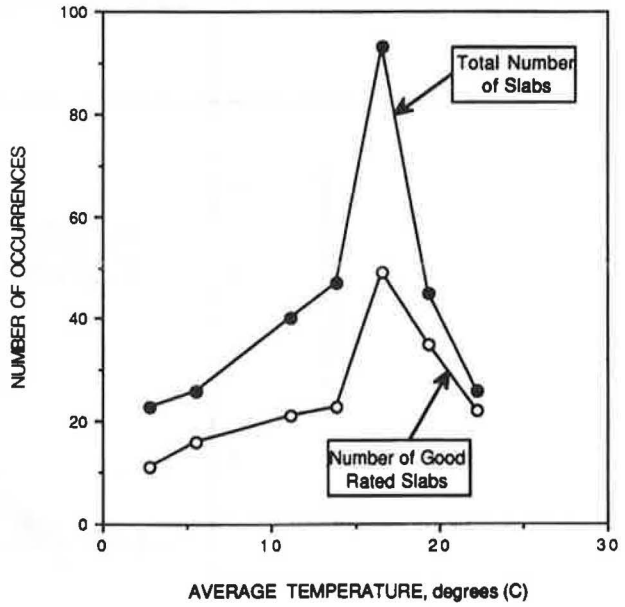

FIGURE 4 Average temperature at the time of the pour versus number of slabs in the field.

temperature and humidity chamber for 24 hours. The fracture specimens were prepared in the same manner as the special molds [described in detail in Fang et al. (*11*)]. At the end of the initial setting period, the specimens were removed from the molds and placed in the appropriate curing environments. It should be noted that all of the results reported as 1-day are the measurements made on each specimen at the end of the first day in its assigned curing environment.

The mix water content was varied from 10 to 16 percent (by total weight) and the curing temperature from −20°C to 100°C. One set of fracture specimens was prepared with increasing proportions of air-entrainment reagent with constant mix water content. The humidity was controlled in one case, for which the specimens were cured in a chamber of constant humidity of 95 percent. The temperature in this chamber was maintained at 28°C. One set of specimens was left outside to cure in ambient temperature and humidity, which varied over time. The average of the day and night temperatures over the period of 28-day curing was determined to be about 20°C. The average relative humidity for the same period of time was about 65 percent. One set of specimens was left to air dry in an air-conditioned laboratory. The average day and night temperature was estimated at about 25°C and the relative humidity at about 20 percent. The other sets of specimens were prepared by curing in the oven at 40°C and 100°C and in the refrigerator at −4°C and −20°C. The frozen specimens were left to thaw in room temperature for a few hours prior to testing.

Table 2 presents the statistical evaluation of part of the data obtained for the unconfined compressive and tensile strength tests and the fracture load tests. Coefficient of variance, which is the value of the percent change (in decimal) per unit of sample mean (= standard deviation/sample mean), is selected as the index for variance analysis. In unconfined compressive strength testing, the highest and the lowest coefficient of variances were 0.186 and 0.001. By multiplying these values with their respective means of 56.7 and 80.5 psi, the highest standard deviation is computed as 10.5 and the lowest as 0.08. Similarly, for the fracture load test the highest standard deviation is computed as 0.57 and the lowest as 0.07. The values given in Table 2 represent sampling of 3, in general.

Results

Unconfined Compressive Strength Tests

Figures 5 and 6 show the variation of unconfined compressive strength with duration of curing time and curing temperature for the 16 percent mixing water content specimens. As observed from both figures, the 28-day strengths of specimens cured in the humidity chamber and in the random ambient temperature are higher than those of the specimens cured in other environments. In Figure 6, the variations in the 1-day strength with respect to various curing environments are significantly less than the variations observed with the 7- and 28-day strength values. The higher strengths developed at median temperatures with relatively high-humidity environments. The air-dried specimens, cured at a median temperature (25°C) but in a low-humidity envirionment (25 percent), did not show as high a strength gain as the other two. These results show the positive influence of high humidity on the unconfined compressive strength of the material. This finding is expected because a high-humidity environment makes available the necessary water for pozzolanic and cementatious reactions to continue without excessive evaporation. As observed from Figure 5, there is little but consistent increase of strength in specimens cured at low temperatures (−4°C and −20°C). This may be due to low rate of evaporation of water at these temperatures. Oven curing at 40°C does not appear to produce much increase in strength; however, the 28-day

TABLE 2 COEFFICIENT OF VARIANCE FOR STRENGTH AND FRACTURE RESISTANCE DATA FOR 28-DAY CURED SPECIMENS

MIX WATER CONTENT (%)	CURING ENVIRONMENT						
	Indoor	40°C	100°C	-4°C	-20°C	Outdoor	Humidity Cham.
	UNCONFINED COMPRESSIVE STRENGTH						
10	0.071	0.186	0.015	0.001	0.113	0.061	0.125
12.5	0.132	0.004	0.030	0.032	0.040	0.111	0.012
16	0.063	0.017	0.097	0.074	0.049	0.137	0.013
	FRACTURE LOAD						
10	0.018	0.121	0.086	0.111	0.050	0.097	0.069
12.5	0.102	0.023	0.152	0.059	0.064	0.086	0.067
16	-	0.049	0.114	0.209	0.009	0.070	0.024
	UNCONFINED TENSILE STRENGTH						
12.5	0.069	0.010	0.037	0.088	-	0.025	0.106

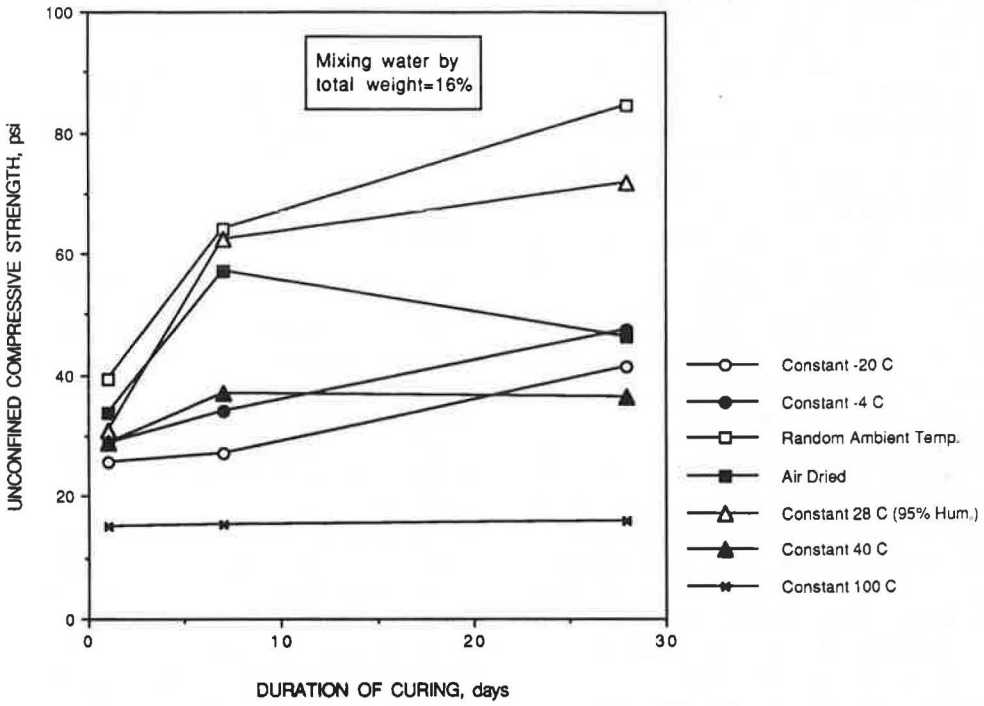

FIGURE 5 Variation of unconfined compressive strength versus duration of curing for various curing temperatures (mix water content = 16 percent).

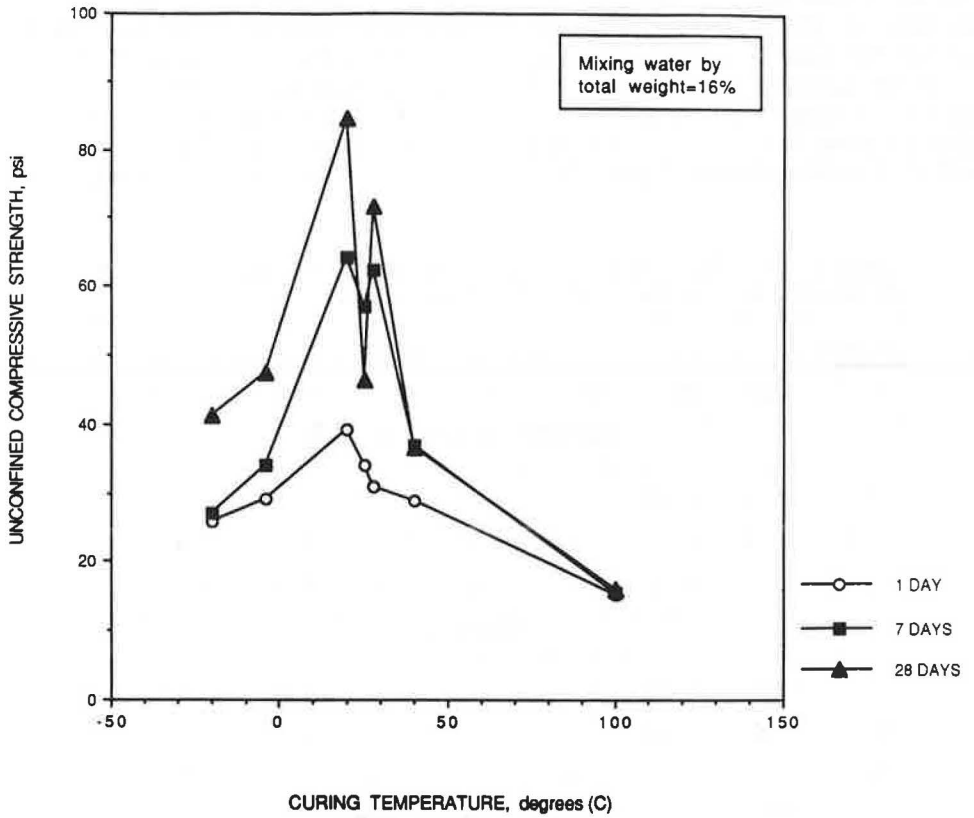

FIGURE 6 Variation of unconfined compressive strength versus curing temperature (mix water content = 16 percent).

strength of these specimens is not significantly different from the other low-strength values. The extreme temperature of 100°C produced the lowest-strength materials, possibly because of the very fast rate of water evaporation. This finding is supported by little or no change in the strength of the specimens cured longer (7 and 28 days) at that temperature.

Figure 7 shows the variation of 28-day unconfined compressive strength with mix water content. There appears to be a general trend in strength reduction with increasing water content for most curing temperatures except the random ambient temperature. This trend may be due to experimental error for the 10 percent water mixed specimens or the degree of fluctuation of ambient temperature and humidity during the curing period of these particular specimens which promoted the low strength. Nevertheless, the general trend of decreasing strength with increasing mix water content is consistent with the behavior of other cement-based composite materials. In general, an amount of water exceeding that needed for hydration reactions may bring about segregation of the mixture and excessive evaporation from the surface, which promotes surface cracking. Both of these occurrences have been known to reduce strength of cement-based composite materials.

Unconfined Tensile Strength Tests

Figure 8 illustrates the variation of unconfined tensile strength with curing time for the specimens with 12.5 percent mix water content. The data show trends similar to unconfined compressive strength data. The highest 28-day strength is observed with specimens cured in the humidity chamber. The difference between the 28-day unconfined tensile strength values obtained for the humidity chamber specimens and the others is quite significant. In general, the unconfined tensile strength values appear to more or less attain a maximum value after 7 days, and the 28-day strengths do not vary appreciably from that value. This may not be necessarily true for the specimens cured in the humidity chamber. The extreme temperatures of curing resulted in low tensile strength similar to the compressive strength. It is interesting that the specimens left outside to cure at random ambient temperature and humidity did not show appreciable increase in tensile strengths over time as they did in compressive strengths.

Figure 9 shows the 28-day tensile strength variation with mix water content for all curing conditions. This figure also shows that the random ambient conditions consistently produced lower tensile strengths than the constant humidity and temperature conditions. In all cases, the tensile strength dropped with increasing mix water content. Overall, the development of both compressive and tensile strengths of the material appears to be strongly influenced by the maintenance of an adequate amount of water in the mixture for continuation of hydration reactions, which is controlled by rate of evaporation of water and the mix water content (water-cement ratio). The compressive strengths do not seem to be as adversely affected by fluctuation of humidity as do the tensile strengths.

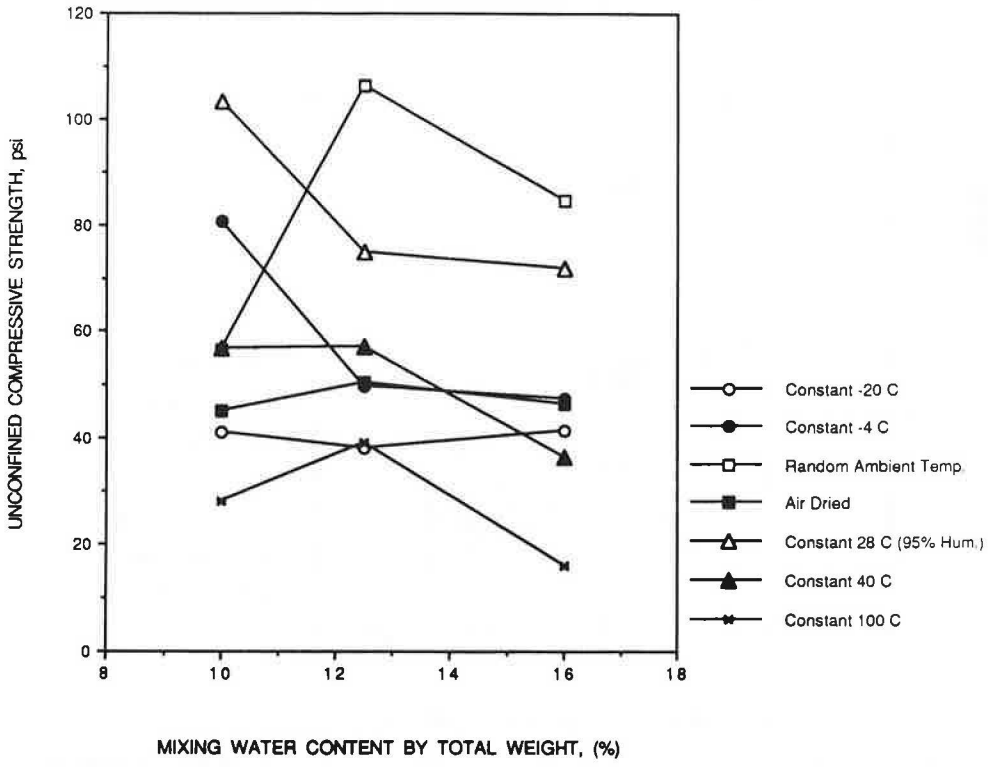

FIGURE 7 Variation of unconfined compressive strength versus mix water content for 28-day cured specimens.

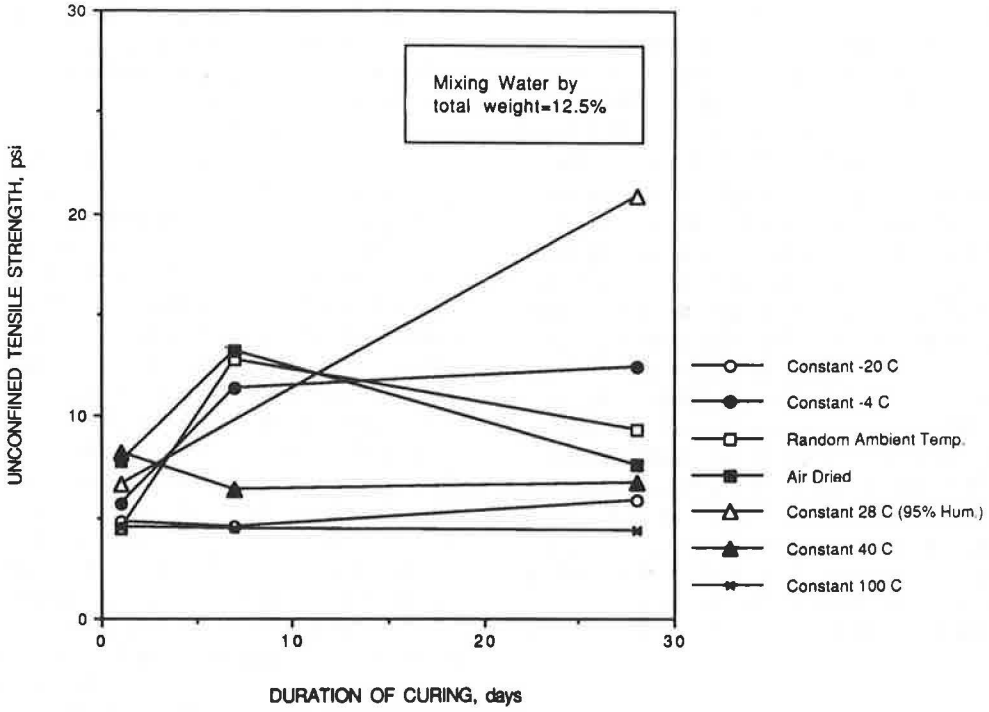

FIGURE 8 Variation of unconfined tensile strength versus duration of curing for various curing temperatures (mix water content = 12.5 percent).

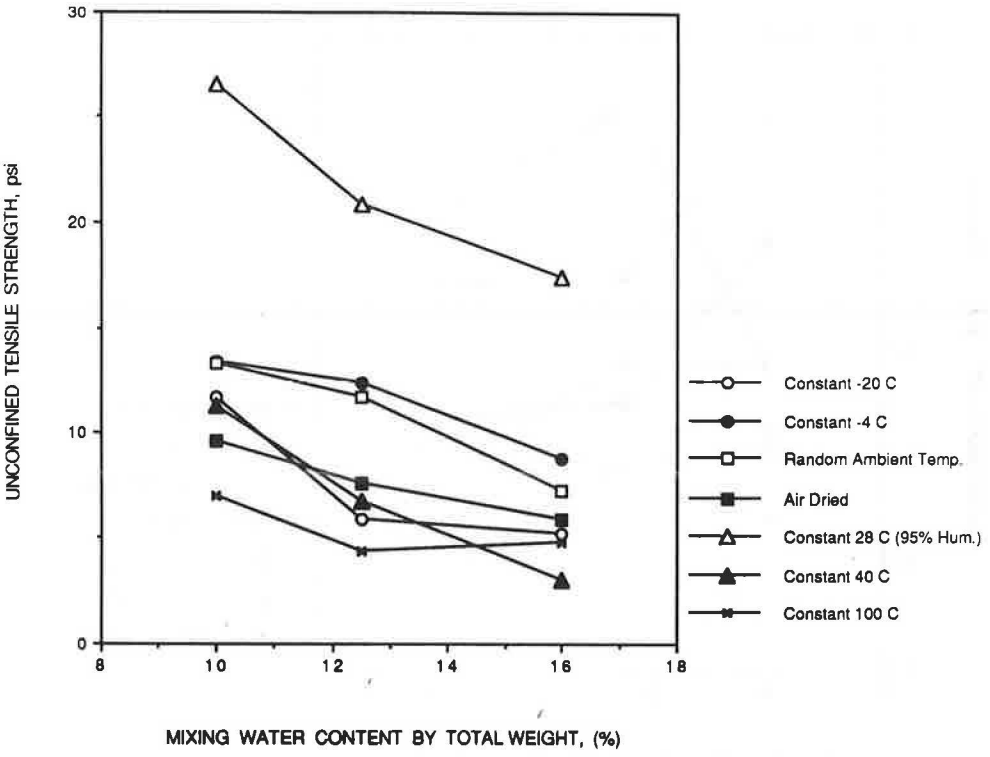

FIGURE 9 Variation of unconfined tensile strength versus mix water content for 28-day cured specimens.

Fracture Load Tests

Figure 10 shows the variation of fracture load versus curing time for the specimens with a 16 percent mix water content. The samples cured in the ambient temperature (20°C) and relative humidity (65 percent) environment apparently are far more resistant to cracking than the samples cured otherwise. Unlike the results of the strength tests, fracture load does not necessarily appear to be influenced by constant high-humidity curing. Specimens cured in the humidity chamber exhibited lower fracture loads than expected. This finding may be due to the lubrication and softening of preexisting microfissures on the surface and near the precrack region by moisture migration from the environment. This effect could have caused somewhat exaggerated consequences for the fracture specimens because of their small size and thin cross-sections.

Figure 10 shows that fast evaporation of water reduces the fracture resistance, as exemplified by the results for the specimens oven-cured at 100°C. The air-dried (25°C, air conditioned, low humidity of 20 percent) specimens also showed low fracture loads, probably because of high-moisture gradients and thus faster drying. Both of the sets of specimens cured at low temperature exhibited some increase in strength over time. This increase was more significant for −20°C samples than for the −4°C samples because humidity loss from the surface would be relatively faster for the −4°C samples. It should be noted, however, that the relative humidity in the refrigerator and in the oven would vary depending on the number of freshly prepared specimens occupying the space. Therefore, fluctuations in data are probable and are difficult to interpret without humidity measurements. Consequently, the higher resistances observed for the 40°C over-cured specimens may be the result of a suitable humidity environment that reduced the moisture gradients.

One of the major causes of cracking is the volume change that a solidified mass can undergo. Water is often the major agent that causes volume change and thus internal stress in such materials. Large moisture gradients and build-up of differential pore water pressures caused by these gradients facilitate cracking. The fast rate of evaporation of water may create large moisture gradients and therefore promotes cracking by reducing the fracture resistance as indicated by the results. Another cause of cracking and deterioration of solidified systems is the crystallization of salts below the surface of the solid as the evaporation of the pore water occurs. Typical damage includes powdering and spalling of the surface, which may deepen progressively as porosity increases (*16*). The faster the water evaporation from the surface the more likely the formation of crystals, caused by increased concentration of the solute underneath the surface, and fracturing and spalling of the surface.

The results of the fracture load tests appear to support the described assessment. Figure 11 shows the variation of fracture load with increased water content for specimens cured for 28 days. Although there are no marked trends of strength variation for each curing environment, the specimens that experience relatively high-moisture gradients, such as the oven-cured and air-dried specimens, exhibit lower fracture resistances in general. The specimens cured in low moisture gradient environments, such as the ambient condition, constant humidity specimens and the refrigerator-cured specimens, exhibit higher fracture resistances in general.

There is a consistent decrease of the fracture resistance for the specimens cured at −20°C and 100°C and for the air-dried

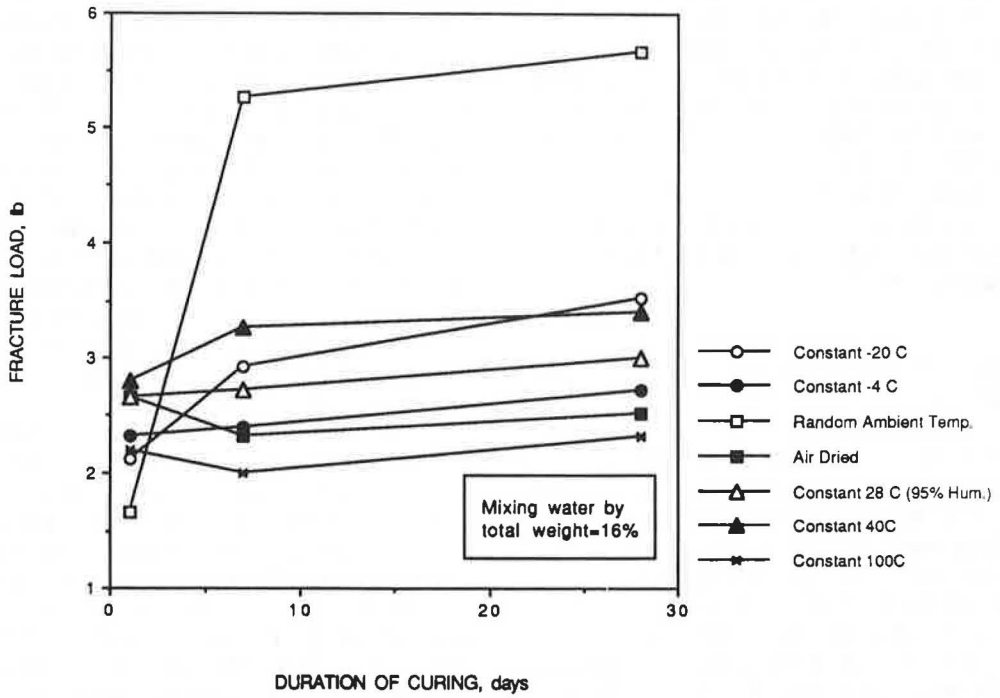

FIGURE 10 Variation of fracture load versus duration of curing for various curing temperatures (mix water content = 16 percent).

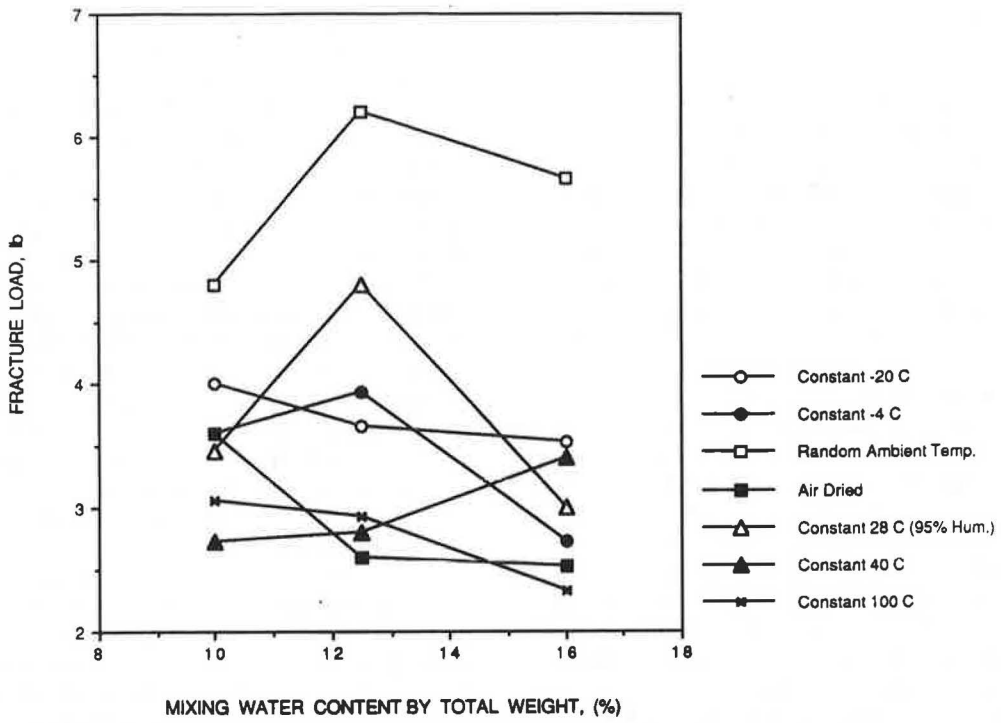

FIGURE 11 Variation of fracture load versus mix water content for 28-day cured specimens.

specimens with increasing water content. Because the humidity can be considered more or less constant for these environments, these results can be less difficult to interpret. In these experiments, the water contents of 10, 12.5, and 16 percent correspond to approximate water-cement ratios of 0.63, 0.78, and 1.00. Increasing water-cement ratio makes more water available to freeze and thus causes increased internal stresses and reduced fracture resistance. Also, as the water content increases, there will be more excess water to evaporate from the surface, therefore promoting larger volume changes and shrinkage. More water would increase the fluidity of the mixture and therefore could promote segregation of the aggregates. Both the tensile strength and the fracture data show similar trends for the three environments with increasing water in the mixture, the causes of which may be due to the factors discussed.

Effect of Additives on Unconfined Compressive Strength and Fracture Load

The base mixture contained approximately 0.046 percent air-entrainment reagent and 0.196 percent superplasticizer reagent by weight of the cement added. Figure 12 shows the influence of increased percentage of air bubbles (percent air-entrainment reagent) on the 28-day UCS of the specimens with 12.5 percent mix water content. In general, increased air content, or reduced saturation, increased the compressive strength resistance when it was added at the design proportion of 0.046 percent by weight of cement. When the proportion was doubled or no reagent was applied, the strength reduced. The most significant variation was observed with the specimens cured at ambient temperature and humidity. There was little or no change in the strength of the frozen specimens with the application of the reagent. Similar trends were observed with the fracture load results given in Figure 13. However, this time, the largest variations were observed with the specimens that were frozen and cured in the humidity chamber, whereas there was no significant variation with the results of the ambient condition specimens. In the overall analysis, results appear to be inconclusive and more tests are necessary to study the effect of water content, humidity, and cyclic freeze-thaw on air-entrainment treatment at larger percentages of the reagent. However, the results of majority of the tests, both the unconfined compressive strength and the fracture load tests, indicate that there may be an optimum proportion of the reagent that will result in higher strength and fracture resistance of the solidified mixture.

Figures 14 and 15 show the variation of unconfined compressive strength and fracture load with increasing percentage of superplasticizer reagent in the mixture. Figure 14 shows that the addition of a proportion of the reagent twice that of the base amount (0.196 percent by weight of cement) results in either no change or reduction in strength. The trends in Figure 15 are somewhat difficult to interpret in the absence of more data. However, in general, addition of the superplasticizer appears to either produce little change or decrease the fracture load. The reductions in unconfined compressive strength and fracture resistance are most evident with the results obtained for specimens cured at ambient temperature and humidity. The highest strengths and fracture resistances are also measured for these specimens. It is interesting that when the superplasticizer is added in excess, the unconfined compressive strength and the fracture resistance values come

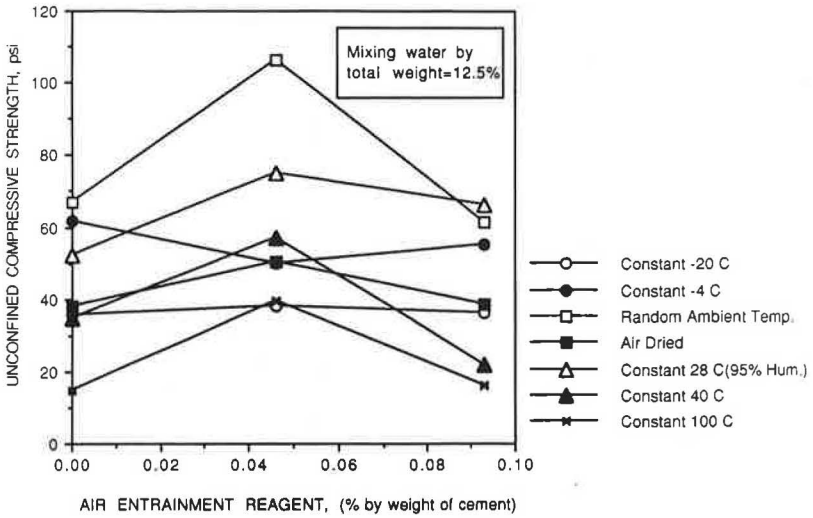

FIGURE 12 Variation of unconfined compressive strength with percent air-entrainment reagent in the mixture for 28-day cured specimens (mix water content = 12.5 percent).

very close to each other for the specimens cured at constant humidity and temperature and those cured at ambient humidity and temperature. Overall, addition of a superplasticizer does not appear to result in high strengths and fracture resistances at the percentages added to the mixture. However, both of the additives, the air-entrainment and the superplasticizer reagents, may significantly improve the durability of the solidified mixture. This possibility requires further evaluation.

SUMMARY AND CONCLUSIONS

The following conclusions were drawn from this study:

1. The solidified product of a steel industry waste sludge may be a viable material to reuse.

2. The process using waste materials (filter cake, slag) mixed with water, cement, and surface-reactant admixtures created a concrete-like material, fairly low in permeability (10^{-7} cm/sec) and moderate in unconfined compressive strength (120 psi).

3. Laboratory-measured durability of the material revealed 10 percent weight loss upon 12 cycles of freeze-thaw, which is within the acceptable limit for most construction purposes. However, when the material was used as an interim cover for a dewatered waste lagoon the actual field performance did not confirm the laboratory durability measurements.

4. Further investigations showed that random field cracking and spalling of covers poured in 1-ft-thick sections may be caused by the variations in temperature, curing conditions, and mixture formula at the time of each pour.

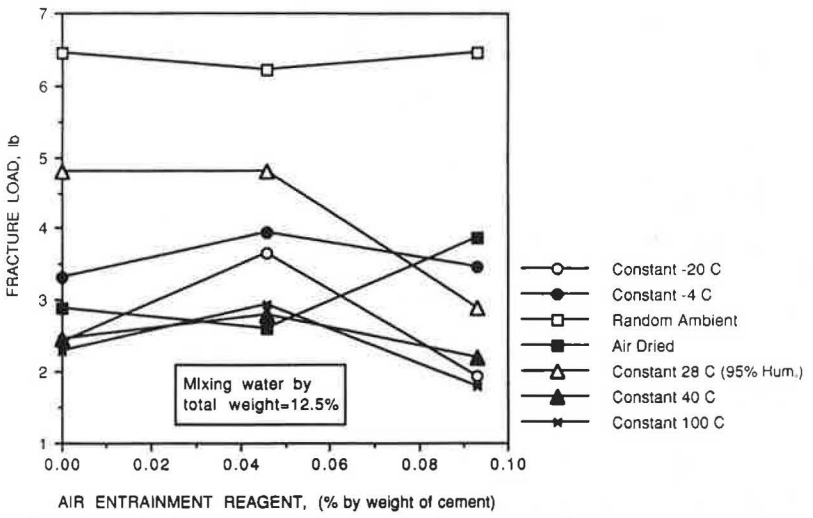

FIGURE 13 Variation of fracture load with percent air-entrainment reagent in the mixture for 28-day cured specimens (mix water content = 12.5 percent).

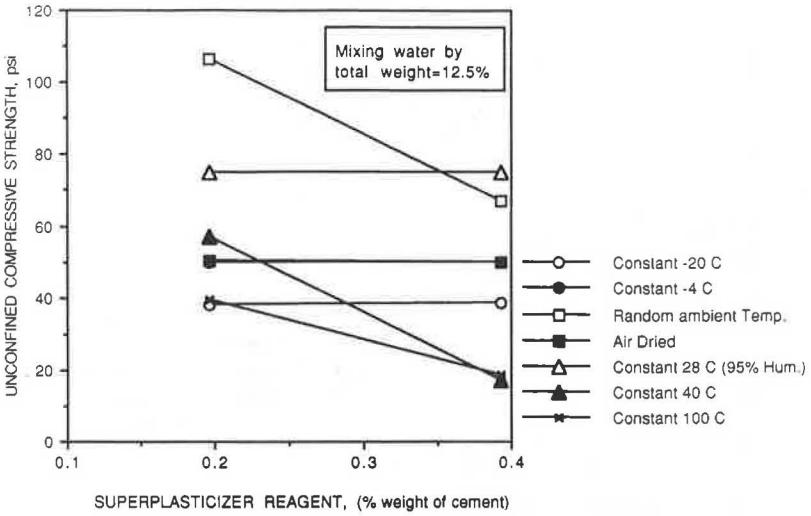

FIGURE 14 Variation of unconfined compressive strength with percent superplasticizer reagent in the mixture for 28-day cured specimens (mix water content = 12.5 percent).

5. A series of tests involving unconfined compression, unconfined penetration, and fracture load tests showed that the curing conditions that may bring about high compressive and tensile strengths may not be favorable for the development of fracture resistance of the material.

6. The unconfined compressive and tensile strength of the material appeared to be strongly influenced by constant high-humidity curing at moderate temperatures.

7. The fracture resistance appeared to be more influenced by rate of evaporation of water. The high- and low-humidity conditions appeared to cause poor fracture resistance, whereas reduced temperatures and average humidity improved the measured fracture load. The fracture load was measured using an ASTM test method standardized for metals and adopted for composite materials in recent years.

8. Increasing the mix water content appeared to lower both the strength and fracture resistance.

9. The results obtained by varying the proportion of air-entrainment reagent indicated that there may be an optimum proportion of this additive that produces the highest values for both strength and fracture resistance in general.

10. Increasing the percentage of superplasticizer reagent in the mixture appeared to generally decrease or have little effect on the strength and fracture resistance of the material.

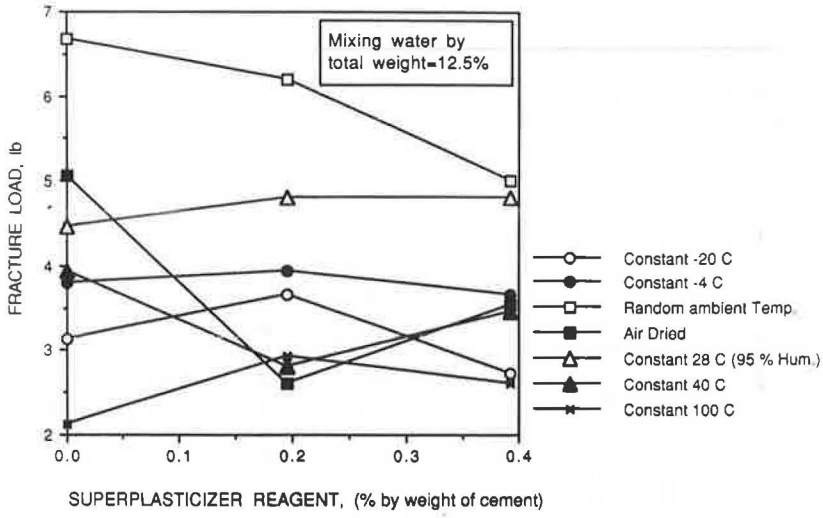

FIGURE 15 Variation of fracture load with percent superplasticizer reagent in the mixture for 28-day cured specimens (mix water content = 12.5 percent).

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Publication of this paper sponsored by Committee on Soil and Rock Properties.