Fuzzy modeling for contaminated soil parameters

T.S. Umesha, S.V.Dinesh, and M.A.Jayaram

Abstract— Soil waste interaction can affect almost all the properties of soil. The unintended modification of soil properties due to interaction with pollutants can lead to alteration in physico-chemical properties such as pH and specific surface area of soil which in turn reduces the unconfined compressive strength of soil. The determination of soil properties due to acid contamination is highly ambiguous due to the complex behavior of soils. The fuzzy set theory provides a powerful tool for modeling uncertainty associated with vagueness and imprecision. The MATLAB fuzzy toolbox was used for the design of the fuzzy model. The experimental data is modeled in four distinct steps. In the first three steps, one antecedent and one consequent model is developed. In the fourth step, two antecedents and one consequent model is developed. The important parameters such as acid concentration, pH, specific surface area and unconfined compressive strength were considered. The available results from experimental work were compared with the outcome of fuzzy system model. It is observed that the results of the developed Fuzzy Inference System are comparable to the experimental results and the fuzzy model is applicable.

Keywords— Acid concentration, pH, specific surface area, unconfined compressive strength, Fuzzy inference system, Fuzzy model.

I.INTRODUCTION

Industrialization, high population growth and uncontrolled exploration of natural resources have resulted in environmental degradation, bringing in unanticipated changes in the engineering behavior of soils.

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Pollution has direct or indirect effects on soil properties. The alteration of the physical, mechanical and chemical properties of the soil in the vicinity of industrial plants occurs mainly as a result of their pollution or contamination by the industrial waste disposed. The acid contamination of soil adversely affect the geotechnical properties of soil. The mechanical behavior of soils predominantly depends on mineralogical composition, physicochemical interaction between particles, inter particle forces, pore fluid chemistry and soil structures. Abdullah Assa'ad [1] investigated tilting of phosphoric acid storage tanks in a chemical fertilizer factory in Jordan. Grzegorz Jozefaciuk and Grzegorz Bowanko [2] reported the effect of acid attack on the crystal structures of aluminosilicate minerals. Ramesh et al [3] have reported the effect of phosphoric and sulphuric acids on the compaction and strength properties of black cotton soil. Sivapullaiah et al [4] have reported the effect of sulphate on strength behavior of black cotton soil. Laredj.et al [5] has reported the effect of chemical solutes concentration changes on deformation behavior of expansive soil. Sridharan et al [6] reported the heaving of soil in a fertilizer plant due to phosphoric acid.

Complexity in the world generally arises from uncertainty in the form of ambiguity. The conventional approaches based on analytical techniques for predicting the behavior of such systems can prove to be very difficult in order to cope with the complexity of the real-world system. In dealing with such systems, one has to face a high degree of uncertainty and tolerate imprecision. The conventional models based on numerical analysis have characteristics of precision, whereas soft computing approaches have characteristics of approximation. Soft computing includes fuzzy logic, neural networks, probabilistic reasoning and genetic algorithms. These techniques or a combination of these techniques are used to design intelligent systems. Neural networks provide algorithms for learning, classification and optimization. Fuzzy logic deals with capturing precision and reasoning on a linguistic level. Probabilistic reasoning deals with uncertainty. There are substantial overlaps between neural networks, fuzzy logic and probabilistic reasoning, but they are complimentary to each other.

There is rapid growth in the application of fuzzy logic in recent years. Fuzzy logic provides the ability to mimic the human mind to effectively employ modes of reasoning that are approximate rather than exact. In hard computing, decisions are based on precision, but in soft computing, tolerance and imprecision are explored in decision making. In fuzzy logic mapping rules are specified in terms of words rather than numbers. Another basic concept in fuzzy logic is the fuzzy if-then rule. In most applications, fuzzy logic solutions are a translation of human solution and it can model nonlinear functions of arbitrary complexity to a desired degree of accuracy. Fuzzy logic is a convenient way to map an input space to an output space and is one of the tools to model a multi-input, multi-output system.

Thus it is known that all types of acids can influence the behavior of soils, though by different mechanisms. The determination of soil properties due to acid contamination is highly ambiguous due to the complex behavior of soils. It may be necessary, with the help of previous experience, to utilize several additional linguistic expressions for the definition of related soil properties. Therefore, it is necessary to design a decision support system for the determination of soil properties under uncertain conditions. The fuzzy set theory provides a powerful tool for modeling uncertainty associated with vagueness and imprecision. Consequently, fuzzy logic provides an efficient way of handling the uncertainty for complex systems. Akbarazadeh et al [7] have applied artificial intelligence in modeling soil properties. Ali Keshavarzi et al [8] have developed neural network model and fuzzy table look-up scheme to develop a pedotransfer function for predicting soil cation exchange capacity using easily measurable characteristics of clay and organic carbon. AmirsAmid et.al [9] have used Hierarchical fuzzy inference system for assessing soil vulnerability to heavy metal contamination.

In the present work a detailed experimental investigation is carried out to study the effect of acid contamination of pore fluid. The contaminants used are hydrochloric, phosphoric and sulphuric acids. The effect of contamination on pH, specific surface area and unconfined compressive strength characteristics of Black cotton soil is investigated. Based on the experimental results an attempt is made to develop a model using fuzzy logic.

II. MATERIALS

Black cotton soil was collected from Gulbarga, in Karnataka state. Table 1 shows the Geotechnical properties of this soil. This is an expansive soil with a liquid limit of 80. It has 60 percent clay, 20 percent silt, 15 percent sand and 5 percent gravel. This can be classified as clay of high compressibility (CH) as per IS classification. In order to study the effect of acids on the properties of soil, the following three acids in concentrations as indicated are considered. In addition tests have been conducted using water as pore fluid that has a neutral pH.

(1) Hydrochloric acid (1.25%, 2.5%, 5%, 10% & 15%)
(2) Phosphoric acid (1.25%, 2.5%, 5%, 10% & 15%)
(3) Sulphuric acid (1.25%, 2.5%, 5%, 10% & 15%)

Table I Geotechnical properties of Black cotton soil

Sl. No.	**Properties**	**Value**
1	Particle size analysis	
	Gravel (%)	5
	Sand (%)	15
	Silt (%)	20
	Clay (%)	60
2	Liquid limit (%)	80
3	Plastic limit (%)	28
4	Plasticity index	52
5	Shrinkage limit (%)	16
6	Specific gravity	2.70
7	Compaction Characteristics	
	Optimum Moisture Content (%)	25
	Maximum dry density (kN/m^3)	14
8	Soil Classification	CH

III. PREPARATION OF ACID CONTAMINATED SOIL

The soil was mixed with 2.5, 5, 10 and 15 percent of hydrochloric, phosphoric and sulphuric acid. The soil was thoroughly mixed with acids and uniform acid distribution was ensured. The contaminated soil was then transferred to polythene bags and kept in the desiccator before testing.

IV.EXPERIMENTAL INVESTIGATION

The details of experimental investigation carried out are shown in Table 2. The concentration of acids was varied from 1.25 to 15 percent by volume and for these percentages pH, specific surface area and unconfined compressive strength tests were carried out as per the relevant IS codes of practice. Water-acid solution was prepared and mixed with soil and left for sufficient time for maturation that in any case not less than 1 hr. The reported results are the average results obtained from three tests. The results of experiment are shown in Table 3.

Table 2 Details of experimental investigation

Sl.No.	**Type of acid/water**	**Pore water concentration (Water: Acid)**	**Tests carried out**
1	Water	100:0	pH, specific surface area and unconfined
2	Hydrochloric acid (HCl)	98.75:1.25 97.5:2.5	
3	Phosphoric acid (H_3PO_4)	95:5 90:10	

4	Sulphuric acid (H_2SO_4)	85:15	compressive strength.

Table 3 Black cotton soil properties for different pore fluid contamination

Pore fluid concentration	**pH**	**Specific surface area m^2/gm**	**Unconfined compressive strength (kN/m^2)**
Water	7.62	282.5	207
1.25% HCl	7.6	275	166
2.5% HCl	7.58	272.5	128
5% HCl	7.53	262.5	98.9
10% HCl	7.48	250	87.4
15% HCl	7.35	205	69.1
1.25% H_3PO_4	7.4	265	163
2.5% H_3PO_4	7.3	260	127
5% H_3PO_4	7.206	240	100.5
10% H_3PO_4	6.908	225	81.1
15% H_3PO_4	6.307	215	75.9
1.25% H_2SO_4	7.44	255	161
2.5% H_2SO_4	7.34	250	130
5% H_2SO_4	7.145	230	103
10% H_2SO_4	6.276	210	95.9
15% H_2SO_4	5.199	200	78.5

V. FUZZY SETS AND MEMBERSHIP FUNCTIONS

Zadeh [10] introduced the term fuzzy logic, which described the mathematics of fuzzy set theory. In fuzzy logic, there is third region beyond true and false. The third value can be best translated as “possible,” and it is assigned a numeric value between True and False.

Fuzzy logic provides the opportunity for modeling conditions that are inherently imprecisely defined. Fuzzy techniques in the form of approximate reasoning provide decision support and expert systems with powerful reasoning capabilities. The permissiveness of fuzziness in the human thought process suggests that much of the logic behind thought processing is not traditional two valued logic or even multivalued logic, but logic with fuzzy truths, fuzzy connectiveness and fuzzy rules of inference. A fuzzy set is an extension of a crisp set. Crisp sets allow only full membership or no membership at all, where as fuzzy sets allow partial membership. In a crisp set, membership or nonmembership of element x in set A is described by a characteristic function $\mu_A(x)$, where $\mu_A(x) = 1$ if $x \in A$ and $\mu_A(x) = 0$ if $x \notin A$. Fuzzy set theory extends this concept by defining partial membership. Fuzzy set A on a universe of discourse U is characterized by a membership function $\mu_A(x)$ that takes values in the interval [0, 1]. Fuzzy sets represent commonsense linguistic labels like slow, fast, small, large, heavy, low medium, high, tall, etc. A given element can be a member of more than one fuzzy set at a time.

The membership function is a graphical representation of the magnitude of participation of each input. It defines how each point in the input space is mapped to a membership value or degree of membership between 0 and 1. It associates a weightage to each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weightage factors to determine their influence on the fuzzy output sets of the final output. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. There are different membership functions associated with each input and output response. Triangular shape is common, but bellshaped, trapezoidal, Gaussian and exponential shapes have been used.

VI. LOGICAL OPERATIONNS AND IF-THEN RULES

Fuzzy set operations are analogous to crisp set operations. The important thing in defining fuzzy set logical operators is that if fuzzy values are assigned value to the extremes 1 (True) or 0 (False), the standard logical operators should hold. The most elementary crisp set operations are union, intersection and complement, which essentially correspond to OR, AND and NOT operators. If A and B are two subsets of U, the union of A and B, denoted as $A \cup B$. contains all elements in either A or B; that is $\mu_{A \cup B}(x) = 1$ if $x \in A$ or $x \in B$, the intersection of A and B, denoted as $A \cap B$, contains all the elements that are simultaneously in A and B; that is $\mu_{A \cap B}(x) = 1$ if $x \in A$ and $x \in B$ and the compliment of A is denoted as $\overline{A}$, contains all elements that are not in A; that is $\mu_{\overline{A}}(x) = 1$ if $x \notin A$, and $\mu_{\overline{A}}(x) = 0$ if $x \in A$. The truth operators for these operators are shown in Table 4

Table 4 Truth tables for AND, OR and NOT operators

AND			**OR**			**NOT**	
A	B	$A \cap B$	A	B	$A \cup B$	A	$\overline{A}$
0	0	0	0	0	0	0	1
0	1	0	0	1	1	1	0
1	0	0	1	0	1		
1	1	1	1	1	1		

In fuzzy logic, the truth of any statement is a matter of degree. The corresponding operators that preserve the results of using AND, OR and NOT is min, max and complement operations respectively. These operators are defined respectively in equation 1 as

$$\begin{aligned}
\mu_{A\cup B}(x) &= \max[\mu_A(x), \mu_B(x)] \\
\mu_{A\cap B}(x) &= \min[\mu_A(x), \mu_B(x)] \qquad (1) \\
\mu_{\bar{A}}(x) &= 1 - \mu_A(x)
\end{aligned}$$

Most applications use min operator for fuzzy intersections, max operator for fuzzy union and 1- μ_A (x) for complementation. Fuzzy inference system consists of if-then rules that specify a relationship between the input and output fuzzy sets. Fuzzy relations present a degree of presence or absence of association or interaction between the elements of two or more sets. A singleton fuzzy rule assumes the form “if x is A, then y is B,” where $x\in$ U and $y\in$ V and has a membership function [0, 1]. The if part of the rule “x is A,” is called the antecedent or premise, while the then part of the rule, “y is B,” is called the consequent or conclusion. Interpreting an if-then rule involves two distinct steps. The first step is to evaluate the antecedent, which involves fuzzifying the input and applying any necessary fuzzy operators. The second step is implication or applying the result of the antecedent to the consequent, which essentially evaluates the membership function.

VII.FUZZY INFERANCE SYSTEM

A fuzzy inference system (FIS) essentially defines a nonlinear mapping of the input data vector into a scalar output, using fuzzy rules. The mapping process involves input/output membership functions, fuzzy logic operators, fuzzy if-then rules, aggregation of output sets and defuzzification. An FIS with multiple outputs can be considered as a collection of independent multiinput, single-output systems.The FIS contains four components; the fuzzifier, inference engine, rule base and defuzzifier. The rule base contains linguistic rules that are provided by experts. It is also possible to extract rules from numeric data. Once the rules have been established, the FIS can be viewed as a system that maps an input vector to an output vector. The fuzzifier maps input numbers into corresponding fuzzy memberships. This is required in order to activate rules that are in terms of linguistic variables. The fuzzifier takes input values and determines the degree to which they belong to each of the fuzzy sets via membership functions. The inference engine defines mapping from input fuzzy sets into output fuzzy sets. It determines the degree to which the antecedent is satisfied for each rule. If the antecedent of a given rule has more than one clause, fuzzy operators are applied to obtain one number that represents the result of the antecedent for that rule. It is possible that one or more rules may fire at the same time. Outputs for all rules are then aggregated. During aggregation, fuzzy sets that represent the output of each rule are combined into a single fuzzy set. Fuzzy rules are fired in parallel, which is one of the important aspects of FIS. In an FIS, the order in which rules are fired does not affect the output. The defuzzifier maps output fuzzy sets into a crisp number. Given a fuzzy set that encompasses a range of output values, the defuzzifier returns one number, there by moving from a fuzzy set to a crisp number.

VIII.DESIGN CONCEPT

The MATLAB fuzzy toolbox was used for the design of the fuzzy model. A simple Fuzzy Inference System (FIS) was used. The important parameters such as acid concentration, pH, specific surface area and unconfined compressive strength were considered. These parameters were categorized into fuzzy inference system FIS1 (acid concentration and pH), FIS2 (acid concentration and specific surface area) and FIS3 (acid concentration and unconfined compressive strength) and FIS4 (pH, specific surface area and unconfined compressive strength). The output of the fuzzy system, unconfined compressive strength, after validation is compared with the experimental results. Based on the data available, the membership functions for acid concentration, pH, specific surface area and unconfined compressive strength were introduced. The experimental values interpreted into linguistic values are shown in Table 5.

Table 5 SOIL PARAMETERS INTERPRETED THROUGH LINGUISTIC MEMBERSHIP FUNCTIONS

Sl.No	**Parameters**	**Linguistic values**		
		Low	**Medium**	**High**
1	Acid concentration (%)	1-3	2-6	4-15
2	pH	5-7	6-9	8-10
3	Specific surface area (m^2/gm)	200 to 220	215 to 250	240 to 290
4	Unconfined compressive strength (kN/m^2)	50 to 100	80 to 130	120 to 200

The experimental data is modeled in four distinct steps. In the first three steps, one antecedent and one consequent model is developed. In the fourth step, two antecedents and one consequent model is developed. In the fuzzy interface system FIS_1 acid concentration is considered as antecedent and pH as the consequent model. The term set in the antecedent space is;

Acid concentration = {Low, Medium, High} (2)

The term set in consequent space is

pH = {Low, Medium, High} (3)

The various fuzzy sets in both spaces are built on average value of acid concentration and pH. To account for non-linearity in uncertainty and impreciseness, Gaussian non-linear fuzzy sets are considered in both the spaces. The membership functions in antecedent and consequent are shown in figure 1 and 2 respectively. The rule bases are of the form;

1. If (Acid_concentration is Low) then (pH is High) (1)
2. If (Acid_concentration is Medium) then (pH is Medium) (1)
3. If (Acid_concentration is High) then (pH is Low) (1)

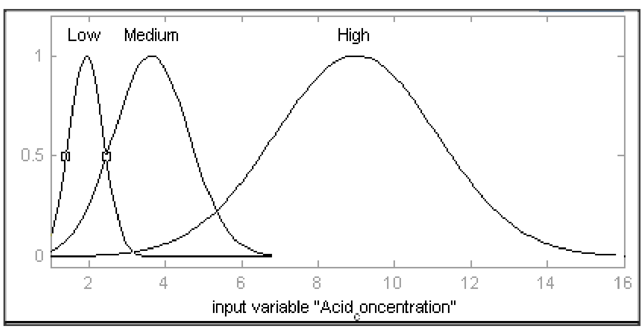

Fig. 1 Input Fuzzy membership functions for acid concentration

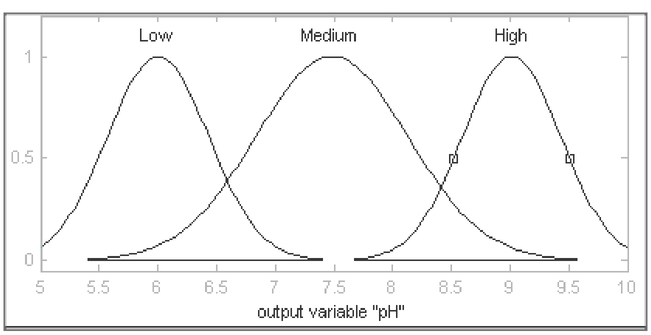

Fig. 2 Out put Fuzzy membership functions for pH

This membership function is evaluated and the available results from experimental work were compared with the outcome of fuzzy system model. Figure 3 compares the experimental results with fuzzy results for acid concentration and pH. It is observed that the results of the developed Fuzzy Inference System are comparable to the experimental results and the fuzzy model is applicable.

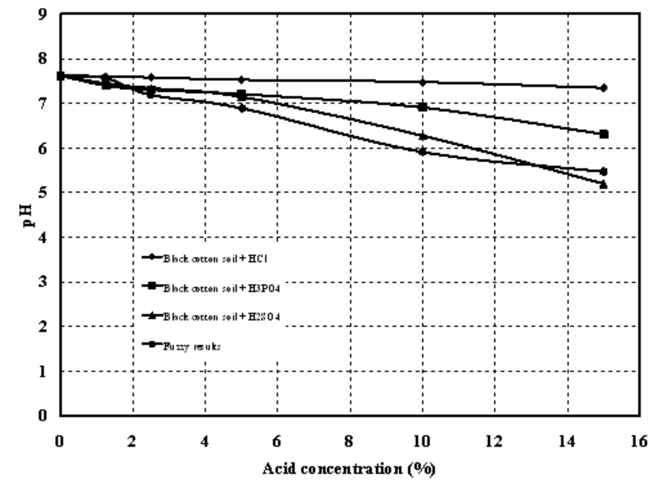

Fig. 3 Experimental results with FIS results for acid concentration and pH

In the fuzzy interface system FIS2 acid concentration is considered as antecedent and specific surface area (SSA) as the consequent model. The term set in the antecedent space is;

Acid concentration = {Low, Medium, High} (4)

The term set in consequent space is

SSA = {Low, Medium, High} (5)

The various fuzzy sets in both spaces are built on average value of acid concentration and SSA. To account for non-linearity in uncertainty and impreciseness, Gaussian non-linear fuzzy sets are considered in both the spaces. The membership functions in antecedent and consequent are shown in figure 4 and 5 respectively. The rule bases are of the form;

1. If (Acidconcentration is Low) then (SSA is High) (1)
2. If (Acidconcentration is Medium) then (SSA is Medium) (1)
3. If (Acidconcentration is High) then (SSA is Low) (1)

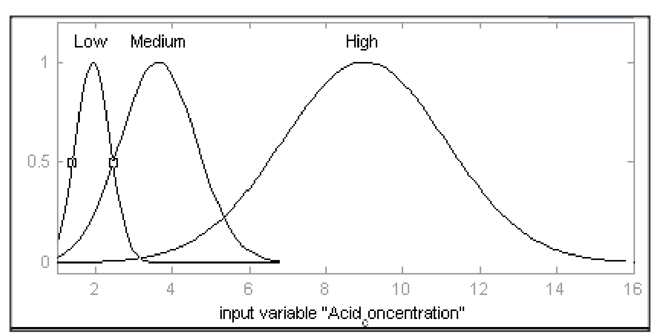

Fig. 4 Input Fuzzy membership functions for acid concentration

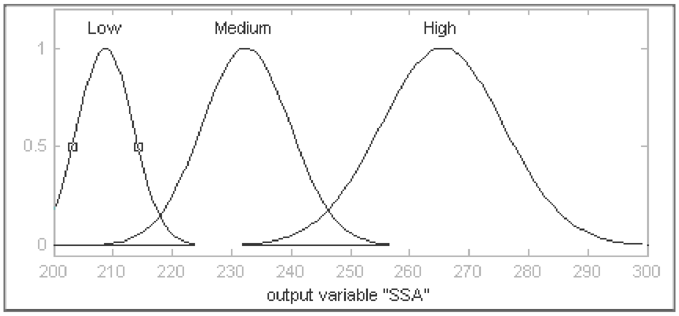

Fig. 5 Out put Fuzzy membership functions for specific surface area

This membership function is evaluated and the available results from experimental work were compared with the outcome of fuzzy system model. Figure 6 compares the experimental results with FIS results for acid concentration and specific surface area. It is observed that the results of the developed Fuzzy Inference System are comparable to the experimental results and the fuzzy model is applicable. It was observed from the experimental results that the reduction in specific surface area of soil was more with phosphoric and sulphuric acids than with hydrochloric acid. Hence there is deviation in specific surface area of soil with hydrochloric acid concentration when compared with specific surface area of soil with phosphoric and sulphuric acids.

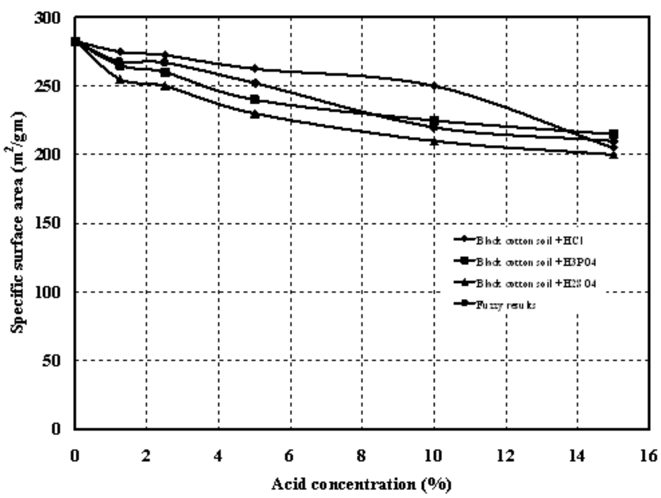

Fig. 6 Experimental results with FIS results for acid concentration and specific surface area

In the fuzzy interface system FIS3 acid concentration is considered as antecedent and unconfined compression strength (UCS) as the consequent model. The term set in the antecedent space is;

Acid concentration = {Low, Medium, High} (6)

The term set in consequent space is

UCS = {Low, Medium, High} (7)

The various fuzzy sets in both spaces are built on average value of acid concentration and UCS. To account for non-linearity in uncertainty and impreciseness, Gaussian non-linear fuzzy sets are considered in both the spaces. The membership functions in antecedent and consequent are shown in figure 7 and 8 respectively. The rule bases are of the form;

1. If (Acidconcentration is Low) then (Unconfinedcompressivestrength is High) (1)
2. If (Acidconcentration is High) then (Unconfinedcompressivestrength is Low) (1)
3. If (Acidconcentration is Medium) then (Unconfinedcompressivestrength is Medium) (1)

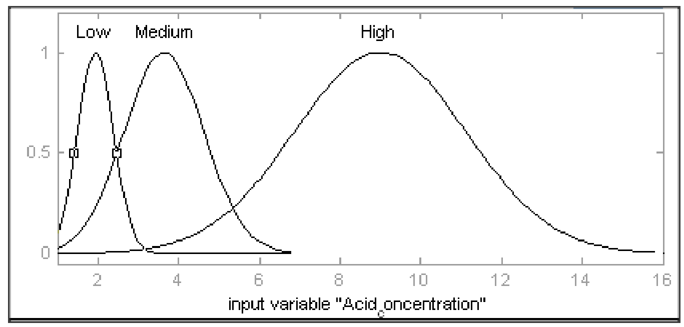

Fig. 7 Input Fuzzy membership functions for acid concentration

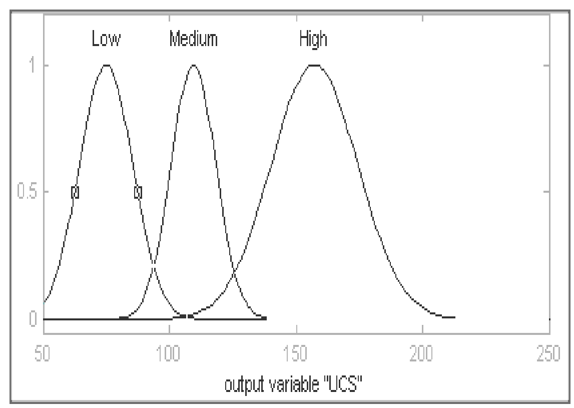

Fig. 8 Out put Fuzzy membership functions for unconfined compressive strength

This member ship function is evaluated and the available results from experimental work were compared with the outcome of fuzzy system model. Figure 9 compares the experimental results with fuzzy results for acid concentration and unconfined compression strength. It is observed that the results of the developed Fuzzy Inference System are comparable to the experimental results and the fuzzy model is applicable.

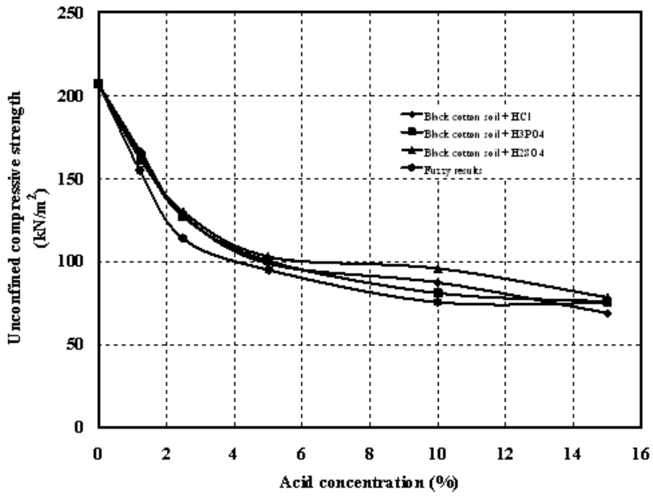

Fig. 9 Experimental results with FIS results for acid concentration and unconfined compressive strength

In the fuzzy interface system FIS4 two parameters pH and specific surface area (SSA) are considered as antecedents and unconfined compression strength (UCS) as the consequent model. The term set in the antecedents space is;

pH = {Low, Medium, High} (8)

SSA = {Low, Medium, High} (9)

The term set in consequent space is

UCS = {Low, Medium, High} (10)

The various fuzzy sets in both spaces are built on average value of pH, specific surface area and unconfined compression strength. To account for non-linearity in uncertainty and impreciseness, Gaussian non-linear fuzzy sets are considered in both the spaces. The membership functions in antecedents for pH and specific surface area are shown in figure 10 and 11 respectively. The membership functions for consequent are shown in figure 12. The rule bases are of the form;

1. If (pH is Low) and (SSA is Low) then (UCS is Low) (1)
2. If (pH is Medium) and (SSA is Medium) then (UCS is Medium) (1)
3. If (pH is High) and (SSA is High) then (UCS is High) (1)

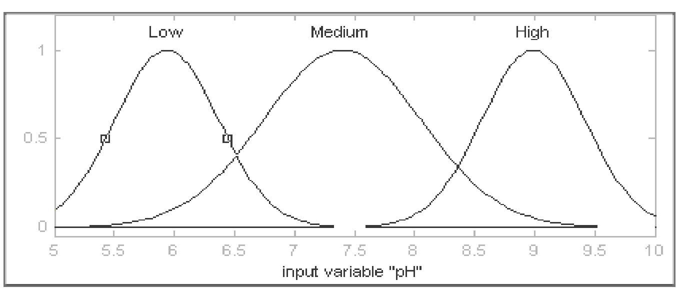

Fig. 10 Input Fuzzy membership functions for pH

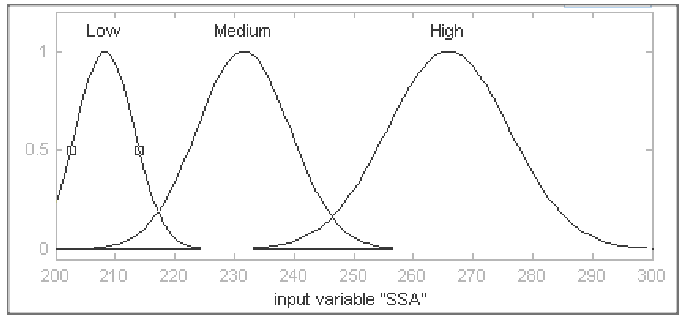

Fig. 11 Input Fuzzy membership functions for specific surface area

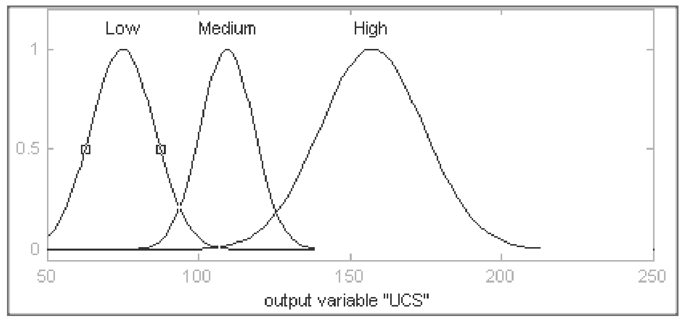

Fig. 12 Out put Fuzzy membership functions for unconfined compressive strength

This member ship function is evaluated and the available results from experimental work were compared with the outcome of fuzzy system model. Figure 13 compares the experimental results with fuzzy results for specific surface area/pH and unconfined compression strength. Figure 14 depicts the Fuzzy relational mapping surface that captures the influence of two input parameters (pH- specific surface area) on unconfined compressive strength of soil. It is observed that the results of the developed Fuzzy Inference System are comparable to the experimental results and the fuzzy model is applicable.

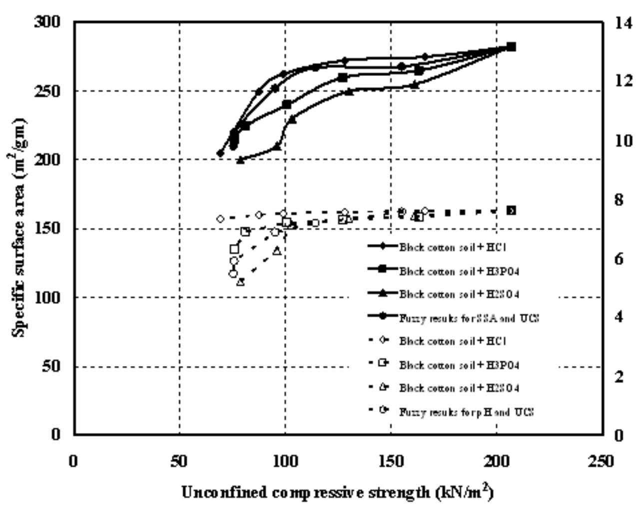

Fig. 13 Experimental results with fuzzy results for specific surface area / pH and unconfined compressive strength

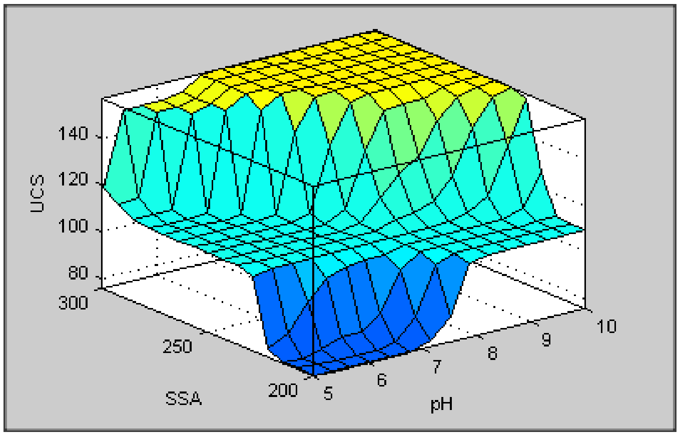

Fig. 14 Fuzzy relational mapping surface in different view angles depicting influence of pH- specific surface area on unconfined compressive strength of soil

IX.CONCLUSION

The quantitative problems in engineering are solved with mathematical models that are in deterministic form. But there are uncertainties due to complex nature of problem. In the paper, soil parameters such as pH, specific surface area and unconfined compression strength that were affected due to acid contamination were selected. The selected soil parameters were introduced to fuzzy inference system and fuzzy inference model was designed. The developed model was validated with experimental results and it was found that the fuzzy model is applicable.

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