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Fuzzy Logic Modelling of Degradation of Cement Mortar in Aggressive Environment

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Abstract*: Degradation of cement mortar takes place in the acidic aggressive environment due to the alkaline nature of hydration compounds of cement. This happens to depend on many factors such as the aggressiveness of environment, time of exposure, mortar mix composition, etc. A study was carried out to appreciate the mechanism of such degradation and an effort has been made to classify various patterns in the degradation process. Due to roles of various factors in such a process, a definite nature and degree of fuzziness creeps in this mechanism. It has been the motive of this study to accept this fact and apply fuzzy logic concepts to such a mechanism comprising of various stages of degradation in the form of different effects which could be visually observed. In this study, it is intended to define degradation stages in cement mortar more rationally by the concept of fuzzy logic and to find out the optimum number of categories in which various types of effects should be divided so that various degradation effects being produced in the material are rightly judged and calibrated with the correct 'structural' condition of the material.

Keywords: Mortar, Sulfate Attack, Visual Rating, Fuzzy Logic

I. INTRODUCTION

Visual observations of samples, being tested in laboratories are made to understand the damage in cement-based construction materials such as cement mortar etc., to understand the damage mechanisms related to the deterioration of such materials in aggressive environments. Such observations also provide us with the progress of deterioration and sequence of the happening of various types of defects in such materials. Various types of such damage sequences in the form of visual ratings have been provided in cement mortar and concrete (Irassar et al. 2009; Zeng at al 2018; Skaropoulou et al. 2009; Tamimi et al 2003; Brown et al 2004; Al-Amoudi 2002; Michael Thomas 2008; Abdelmseeh 2008). Though visual observations are helpful in making us understand the process of damage in cement-based materials, their results are many times of a fuzzy nature. Due to this, it becomes somewhat difficult to provide clear conclusions from the results.

In the case of concrete, many effects have been seen in various stages of deterioration. These have been defined as subsurface cracks (Stock et al 2002), fine cracks (Planel et al 2006), spalling of surface material (Hartshorn et al 1999; Al-Akhras 2006; Zhou et al 2006), blistering of surface (Hartshorn et al 1999; Collett et al 2004), crazing (Al-Dulaijan et al 2003), loosening of material (Zhou et al 2006) etc. It has been appreciated that length expansion takes place in a specimen which may lead to the development of stresses (Hartshorn et al 1999). Sometimes, surface cracks are combined with other effects (Al-Akhras 2006). Effects such as swelling of corners, a complete breakdown of samples, appearance of soft pulpy mass of mortar, debonding of matrix from aggregate particles, extreme distress, onion peeling type degradation of samples have been seen by many researchers in the past (Gallop and Taylor 1996; Planel et al 2006; Hooton 2008; Zhou et al 2006; Al-Akhras 2006; Lee et al 2008). Many other effects such as erosion of faces, change in colour, loss of cohesion, softening of an external layer of mortar specimen have also been reported (Zhou et al 2006; Hartshorn et al 1999; Collett et al 2004; Planel et al 2006; Torres et al 2004; Haynes 2008).

All cements, including the sulfate-resisting cement are vulnerable to sulfate attack (Rasheeduzzafar 1992, Al-Amoudi 1998). Rate and intensity of attack depend on cement type, sulfate type & concentration, quality of material, exposure conditions, etc. (Al-Amoudi 2002). Cement mortar also is subjected to the same types of effects, as in cement concrete, due to cement being the same strength imparting material in both the cases. Many researchers have provided the occurrence of various effects in cement mortar samples with the help of visual observations. (Skaropoulou et al. 2009) have considered the long-term behavior of Portland limestone cement mortars exposed to magnesium sulfate attack. The study has considered various stages of degradation and these stages have been defined in the form of various effects appreciated by visual observations. Nine different effects have been shown and it has been observed by the data of visual observations that these effects take place in the same sequence in various types of cement mortar mixes in the 1.8%$MgSO_4$ solution. It has also been observed that the complete deterioration of mortar mixes takes place at approximately the same time, except only one mix of mortar.

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Effect of the aggressive environment has been reported in the context of Ultrasonic pulse velocity test results and mass loss taking place in aggressive environment.

An average change of ultrasonic pulse velocity values to the extent of 15 to 19% has been shown to have taken place in a time span of 6 to 12 months. Mass loss up to an extent of more than 50% is also reported (Skaropoulou et al. 2009).

Effect of Magnesium sulphate solution on sulfate resistance of geopolymer mortar has been investigated (Elyamany et al, 2018) and the deteriorating visual effects have been correlated with parameters such as weight change, compressive strength, expansion strain, etc. The combined effect of chloride and sulfates has been investigated by (Abdalkader et al 2015) and visual observations have been reported. It has been observed that the effects of deteriorating aggressive environment are first observed in the rounding of edges and corners. Change of mass, color changes and spalling of mass from mortar specimens have also been reported. It is seen that the effects reported by visual observations in the most of the cases are broadly in a uniform sequence. (Al-Dulaijan et al. 2003) have investigated the effect of sulfate environments of various concentrations on cement mortar specimen and have recorded visual observations. Very high concentrations of sulfates, occurring in saline soils, have been considered in the study and strength reduction has been correlated to the visual effects. (Chen et al. 2017) have considered the deteriorating mechanism of plain and blended cement mortars exposed to sulfate attack and has mentioned various effects such as softening, expansion, cracking, spalling and disintegration of cement-based materials. Visual observations in the case of cement mortar have been reported (Hartshorn et al 1999) and similar types of effects have been seen to be happening in all the degrading types of environments. Visual effects on cement mortar specimens have been reported in various types of aggressive environments (Irassar et al 2009, Aye et al. 2011, Al-Amoudi,2002, Kwasny et al.2018, Maes et al 2017, Pastor et al.2018, Planel et al 2006, Zhou et al. 2006, Stock et al 2002). A summary of such details is provided in Table 1 below.

Table- I: Summary of visual observations in cement mortar

Researcher's Name	Curing Environment	Effects recoded after visual examination
Hartshorn et al 1999	*Na_2SO_4 solution*	*No visible deterioration, White powdery coating, crazing of surface, Expansion, cracking and spalling, beginning to spall, extensive spalling, Surface softening, no cracking but some corrosion at edges, Blisters containing grey white mush, beginning to crack, Partial disintegration Cracking and spalling, Disintegration Spalling and softening.*
Al-Amoudi, 2002	*$MgSO_4$ & Na_2SO_4 solution*	*Eating away of the hydrated cement paste and progressively reducing it to cohesionless granular mass leaving the aggregates exposed – reduction of cross-sectional area –decrease in strength, Expansion and cracking, Onion peeling type of scaling or shelling of the surface in successive layers in the form of delamination and cracking*
Stock et al., 2002	*10000 ppm Na_2SO_4 solution*	*No damage, Extreme damage*
Al-Dulaijan et al., 2003	*Sulfate conc. of 1 to 4%*	*No damage, Cracking, minor spalling, spalling of the surface skin at the corners, intense spalling*
Zhou et al., 2006	*1.6 g SO_4 /L*	*Formation of a white mushy deposit on the top surface of the cubes, Blistering, spalling at the corners and edges of the cubes. aggregate exposure, color change, very fine crystals were observed on the surfaces*
Planel et al., 2006	*15 mmol/L of Na_2SO_4 solution*	*Cracking, surface delamination, leached surfaces, surface spalling*
Skaropoulou et al., 2009	*1.8% $MgSO_4$*	*No visible deterioration, some deterioration at corners, deterioration at corners and some cracking along the edges, deterioration at corners and cracking along the edges, cracking and expansion, bulge of surfaces, extensive cracking, extensive spalling, and complete damage.*
Irassar et al., 2009	*Na_2SO_4 & MgSO4 solution*	*No visible deterioration, Deterioration at corners and edges, Cracking along the edges, Extensive cracking and expansion, Spalling and disintegration of surfaces*
Seung-Tae Lee 2009	*$MgSO_4$ Solution*	*Surface damage at the corners of the mortar, white powdery material deposited on the faces of mortars, spalling and cracking at the corners, edges and faces, small spalling only at the corners and edges, some surface damages (i.e., spalling and delamination)*

Aye et al., 2011	*$MgSO_4$ & 10% Na_2SO_4 solution*	*No visual damage, loss of cohesionless particles from the surface of the specimens, no other damages (such as cracking and spalling), weight loss, extensive cracking, efflorescence, loss of cohesionless particles*
Maes et al., 2014	*$MgSO_4$ solution*	*Spalling of the outermost layers, some small cracks, extensive cracking, crumbling., mass changes, spalling of surface layer*
Chen et al., 2017	*10% Na_2SO_4 solution*	*No damage, Salt efflorescence, surface scaling and flaking, cracking, weight loss*
Q. Zeng et al., 2018	*50 g/L Na_2SO_4 and 44.2 g/L $MgSO_4$ Solution*	*No visible deterioration, Some deterioration at corners, Deterioration at corners and the edges, Deterioration at corners and some cracking along the edges, Cracking and expansion along the edges, Serious cracking and expansion, Spalling and expansion of surface, Grey pulp at corners, edges and surface, Amount of grey pulp at specimens, Complete damage*
Elyamany et al., 2018	*10% $MgSO_4$*	*Spalling of edges, change in shape, micro cracks and pores, visible cracks, soft and powdery white deposits on surface which became harder with time, surface erosion, weight loss*
Kwasny et al., 2018	*H_2SO_4 & HCl solutions*	*No sign of discoloration, expansion or cracking on the surface, microcracks, curled, broken, and longitudinal, layer of white precipitates*
Pastor et al., 2018	*15% Na_2SO_4 solution*	*Increase in roughness, crystallization of salts, loss of small pieces of material, and cracks*

II. PROGRAMME OF THE STUDY

It is understood that visual observations of effects in durability studies portray the strength conditions of a material. That is why, visual effects are recorded in such types of studies. In the case of cement concrete, many researchers have specified different visual ratings based on which other characteristics of concrete have been calibrated. It may be appreciated that a particular type of visual effect denotes a range of a particular condition and in that range the 'degree' of that effect is to be further defined based on clarity of information about tests and experience, expertise etc., of the researcher. For example, the effect of color change may be defined as small, medium or a large color change. Boundaries between these sub-effects become fuzzy as many times it may be difficult to put a particular sample in the correct category. Many times, it may be easier to recognize the effect but it may be more difficult to decide the intensity of that effect. In this study, it is intended to find out the optimum number of categories in which various types of effects should be divided so that various effects being produced in the material are rightly judged and calibrated with the correct 'structural' condition of the material.

The present study considered the durability conditions of 1:4 and 1:6 mix cement mortar cubes of size 10 cm side in H2SO4 solution of normality N1 and N2. Fig.1 shows some samples of this study showing different degrees of various effects occurring in samples. In some samples, simultaneous occurrence of various effects can also be recognized. If color change is taken into consideration, it may not be definitely said that all mortar specimens are at the same level of deterioration. Many times, it may not be easy to compare two samples based on a particular effect. In many cases, two or more effects are there in a sample and the decision making about existing degradation may be difficult to be taken. This fact impels for a fuzzy based approach to be taken up.

Fig.1. Cement mortar cubes in different stages of degradation

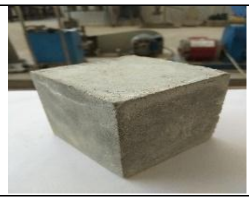

Fig. 2. No visible deterioration

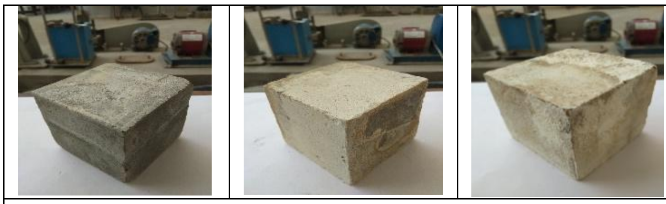

Fig. 3. Efflorescence: low, medium & high

Fig. 4. Color change: low, medium & high

Fig. 5. Falling of edges: low, medium & high

Fig. 6. Falling of corners: low, medium & high

Fig. 7. Surface Roughness: low, medium & high

Fig. 8. Blistering of surface: low, medium & high

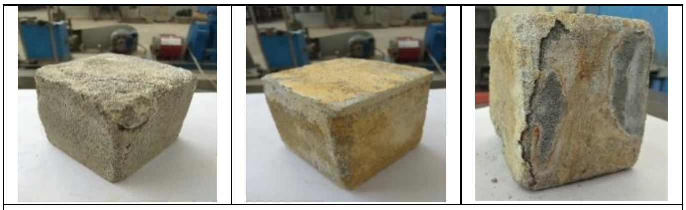

Fig. 9. Cracks: low, medium & high

Fig. 10. Spalling of mass: low, medium & high

Fig. 11. Softening of cubes: low, medium & high

Fig. 12. Complete Damage: low, medium & high

The visual examination of the samples performed on cement mortar at regular intervals of time. Some significant modifications, such as formation of white mushy layer deposited on the surface of the mortar i.e., efflorescence, changes in surface color and texture, formation of coatings, falling of edges and corner, surface roughness**,** blistering of surface, cracking and spalling of mass, softening of cubes and complete deterioration were recorded and are shown in Fig. 3 to Fig. 12 in the form of low, medium and high ratings. Fig. 2 displays a cement mortar sample which is having no signs of visible deterioration. Though such a case may not require any need of fuzzy logic to appreciate a condition of no deterioration, this case is taken here for inclusion of all cases for the sake of complete treatment. To assess the deterioration performance of the cement-based structures, many researches have included a description of the visual appearance of degraded specimens in the form of visual ratings (Irassar 2009) and some of these are presented in Table I. Visual ratings made on the basis of these reported effects should have an optimum number of classes to contain all effects being produced due to degradation. If a visual rating has a large number of classes, many simultaneously occurring effects may not be considered. If only a few classes are provided in the visual rating scheme, effects may not be graded accurately to define degradation of material.

In this study based on fuzzy logic, output confidence in the form of likely accuracy in recoding the actual degradation in a sample is calculated. Mamdani type inference system in MATLAB was used in this study. Two input parameters – degradation classes and site & exposure conditions – are considered. Membership functions for degradation classes are defined in terms of Gaussian functions while those for site & exposure conditions are defined as triangular functions. Three cases of input 1 – degradation classes with 3, 6 and 9 categories – have been considered. Recognition of site & exposure conditions may require human attributes such as expertise, experience and qualification related to deterioration aspects of cement-based materials in aggressive environments. Three categories – poor, average and good – have been prescribed to classify this input. Input 2, based on exposure condition, consists 3 membership function that remain same for all cases. The output has been considered in terms of confidence which can be placed in a situation based on degradation classes and site & exposure conditions. It also is defined in terms of gauss membership functions. Values of 0 and 1 for a particular input / output parameter may respectively show a 'complete uncertain situation' and 'accurately defined situation'.

Output confidence for low-low, low-high, high-low and high-high values of input 1-input 2 values have been determined. Rule view for a test case when the values of confidence in input 1 and input 2 are varied systematically is shown in Fig. 17. Fuzzy inference systems, used in this study, is given below.

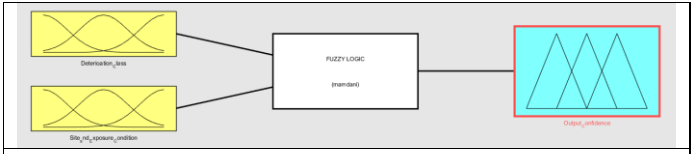

Fig. 13. Fuzzy system with 2 inputs, 1output and 27 rules

III. Fuzzy Inference System

Name='fuzzylogic'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=27
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='deterioration class'
Range=[0 1]
NumMFs=9
MF1='stage1':'gaussmf',[0.04946 0.00576]
MF2='2':'gaussmf',[0.03015 0.1495]
MF3='3':'gaussmf',[0.03075 0.2493]
MF4='4':'gaussmf',[0.02722 0.3645]
MF5='5':'gaussmf',[0.02765 0.4665]
MF6='6':'gaussmf',[0.0272 0.57]
MF7='7':'gaussmf',[0.02913 0.6612]
MF8='8':'gaussmf',[0.0288 0.769]
MF9='9':'gaussmf',[0.09343 1]
[Input2]
Name='site & exposure condition'
Range=[0 1]
NumMFs=3
MF1='poor':'trimf',[-0.4929 -0.0071 0.3651]
MF2='average':'trimf',[0.1576 0.4994 0.8307]
MF3='good':'trimf',[0.634 1.01 1.5]
[Output1]
Name='output_confidence'
Range=[0 1]
NumMFs=3
MF1='poor':'gaussmf',[0.15 0]
MF2='average':'gaussmf',[0.15 0.5]
MF3='good':'gaussmf',[0.15 1]

[Rules]
1 1, 1 (1) : 1 1 2, 2 (1) : 1 1 3, 3 (1) : 1 2 1, 1 (1) : 1 2 2, 2 (1) : 1 2 3, 3 (1) : 1 3 1, 1 (1) : 1 3 2, 2 (1) : 1 3 3, 3 (1) : 1 4 1, 1 (1) : 1 4 2, 2 (1) : 1 4 3, 3 (1) : 1 5 1, 1 (1) : 1 5 2, 2 (1) : 1 5 3, 3 (1) : 1 6 1, 1 (1) : 1 6 2, 2 (1) : 1 6 3, 3 (1) : 1 7 1, 1 (1) : 1 7 2, 2 (1) : 1 7 3, 3 (1) : 1 8 1, 1 (1) : 1 8 2, 2 (1) : 1 8 3, 3 (1) : 1 9 1, 1 (1) : 1 9 2, 2 (1) : 1 9 3, 3 (1) : 1

IV. Membership Functions

Membership functions showing different categories of the input 1 parameter of 3, 6 and 9 visual classes are shown in Fig. 14 to Fig. 16.

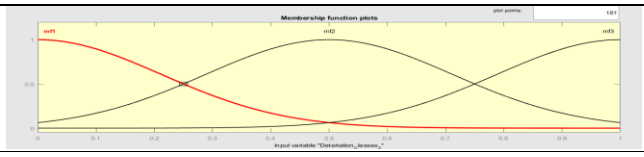

Fig. 14. Membership function for Input1 (3 classes)

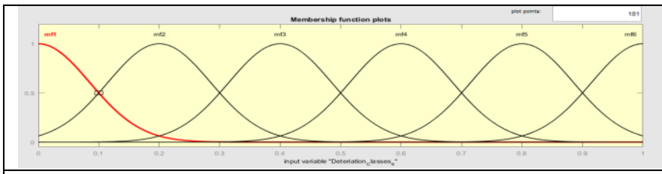

Fig. 15. Membership function for Input1 (3 classes)

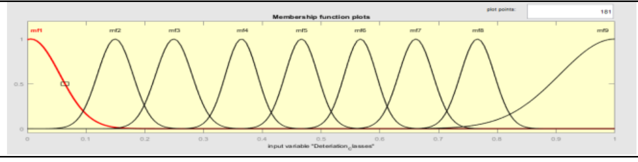

Fig. 16. Membership function for Input1 (9 classes)

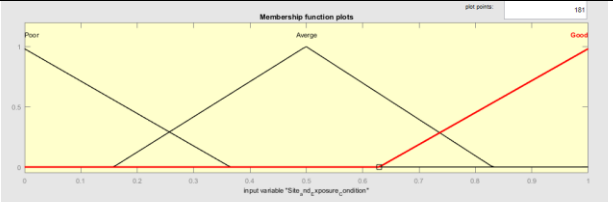

Fig. 17. Membership function for Input2 (3 classes)

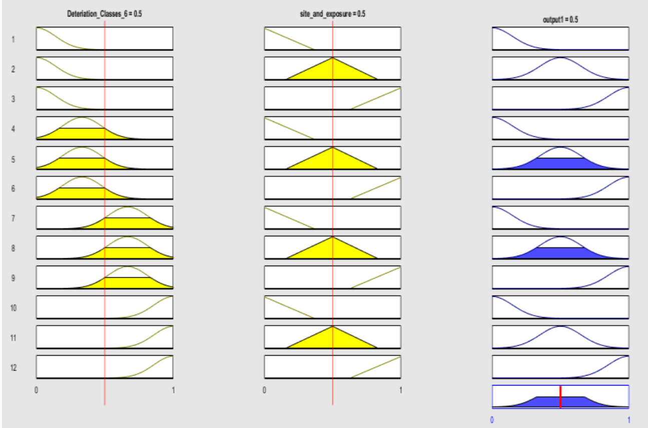

Fig. 18. Rule view for particular values of input and output

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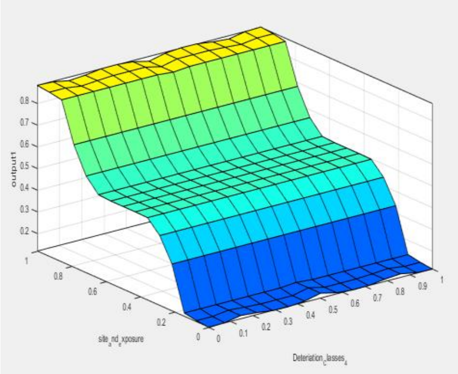

Fig. 19. Surface view

V. RESULT AND DISCUSSION

A particular result, obtained from rule view of MATLAB, is shown in Fig. 17. Surface view for input and output is shown in Fig. 18. In such a diagram, only two input parameters may be considered with the output at a time. From the rule view and surface view it is observed the confidence of output depends, to a great extent, on input 2. This type of variation has been seen in all three cases of same type. It is clearly observed that input 2 affects the confidence in output to a greater extent than input 1. It means output confidence or 'accuracy of decision for characterizing depends on exposure conditions, the availability of information with respect to site & material more than number of categories in a visual rating system. Output confidence with respect to a systematic change of input1 and input 2 has been shown in Table II.

<u>From the data given in Table II, following conclusions may be noted:</u>

Medium output confidence in all the three cases is obtained when value close to 0.5 is given to both input 1 and input 2, as shown in row is 1st row. Output confidence value does not change in all the cases when input 1 has been taken to be very low while input 2 remains as such as, shown in 2nd row. Value of output confidence does not change in all the cases when value of input 1 has been taken to be high while input 2 remains as such, as shown in 3rd row. Value of output confidence lowers down tremendously in all the cases when value of input 1 has been restored as its initial value while input 2 has been assigned a low value, as shown in 4th row. Value of output confidence rises up in all the cases when value of input 1 has been taken as its initial value, while input 2 has been assigned a high value as shown in 5th row.

Output confidence in the results of visual examination in field studies and laboratory, depends on the confidence generated due to the availability of accurate information rather than number of classes in a visual rating system. The meaning of a particular class becomes vague and also the reach of classes becomes very broad, if the number of classes is too low. It may be difficult to accurately select the right deterioration stage for the particular material if visual rating classification system consists of too many classes. In such case, boundaries between adjoining classes become more and more fuzzy. This problem may be understood from the concepts given by (Klir and Yuan 2001), 'opted uncertainty' and 'forced uncertainty' used in fuzzy systems analysis. In the visual rating system, if the number of classes is reduced by merging, it becomes a case of 'opted uncertainty'. For example, if only two stages are there in a visual rating classification system then deterioration may be given either as 'nil' or 'full'. Having too many classes in visual rating also gives an idea of 'Forced uncertainty'. For example, a rating system having too many classes may be dependent on the existence of a crack. In that condition, presence of very minute cracks which may not be observed with the help of available instruments may not help us to designate the appropriate deterioration rating corresponding to that class of cracking.

Some common effects at various stages, given in table I, may be combined and suggested, as given in Table III. The boundaries of the categories still remain fuzzy and these overlap one another by some degree. That is why common effects may be indicated in different classes. It may be seen that color changes appear in stage 2, 3 and 4 but the degree of color change may be different. Likewise, disintegration of samples in different stages comes with different adjectives – partial or complete disintegration. It is suggested that a degradation stage may be allocated to a sample based on all likely visual effects as per that stage in question. All visual effects in a combined way, may indicate the presence of a stage of degradation which, in turn, may point towards a 'structural condition'.

Table- II: Output with variations in input

S. No.	Rating system with 3 classes			Rating system with 6 classes			Rating system with 9 classes		
	Number of classes	Exposure	Result confidence	Number of classes	Exposure	Result confidence	Number of classes	Exposure	Result confidence
1.	0.501	0.512	0.5	0.501	0.512	0.5	0.501	0.512	0.5
2.	0.012	0.512	0.5	0.012	0.512	0.5	0.012	0.512	0.5
3.	0.989	0.512	0.5	0.989	0.512	0.5	0.989	0.512	0.5
4.	0.501	0.001	0.117	0.501	0.001	0.14	0.501	0.001	0.143
5.	0.501	0.998	0.883	0.501	0.998	0.86	0.501	0.998	0.857

Some common effects at various stages, given in table 1, may be combined and suggested, as given in Table 3. The boundaries of the categories still remain fuzzy and these overlap one another by some degree. That is why common effects may be indicated in different classes. It may be seen that colour changes appear in stage 2, 3 and 4 but the degree of color change may be different. Likewise, disintegration of samples in different stages comes with different adjectives – partial or complete disintegration.

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It is suggested that a degradation stage may be allocated to a sample based on all likely visual effects as per that stage in question. All visual effects in a combined way, may indicate the presence of a stage of degradation which, in turn, may point towards a 'structural condition'.

Table-III: Suggested visual rating system for degradation of cement mortar in aggressive environment

Stage	Likely visual effects
1	No visible deterioration, efflorescence, hairline cracks, roughening of surface
2	Cracking due to expansion in material, initial color changes from grey color of cement, spalling of edges & corners of samples
3	Partial disintegration, surface peeling off, extensive softening and spalling, color changes
4	Intense color changes, extensive softening and spalling, reduction of cross section, considerable to complete disintegration

VI. CONCLUSIONS

Following conclusions may be drawn from this study.

1. A visual rating system should be accurate as well as efficient in deciding the degradation stage of a sample. Accordingly, it should contain an optimum number of classes or stages. In this study four classes are found to be necessary and sufficient for the purpose.
2. Every different effect representing degradation should be clearly defined in a visual rating system. Due to fuzzy nature of conditions representing adjoining stages, the use of fuzzy logic is beneficial in such cases of decision making.
3. In deciding deterioration stage for a sample, it should be ensured that the sample conforms broadly to given possible visual effects of a stage.

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