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Internal Erosion Control in Sand-Gravel Mixtures Using MICP

[1] Naufila, [2]Sreevidhya V
[1] P.G. Student, [2] Assistant Professor
[1][2] Department of Civil Engineering, IES College of Engineering, Chitilapilly Trissur, India

Abstract:-- **Earth embankment dams are one of the most commonly constructed hydraulic structures. Seepage induced internal erosion is one mode of failure in in earth filled embankment dams. In this study, the applicability of microbially induced carbonate precipitation (MICP) for internal erosion control is examined in laboratory using sand – gravel mixture of ratio 1:1. A series of internal erosion tests are conducted using a rigid wall downward erosion test apparatus for untreated, 0.2M, 0.4M, 0.6M, 0.8M and 1M specimens. The tests are also conducted for 3 days and 7 days cured specimens. The flow rate of water is varied as low, medium and high flow. Hydraulic conductivity, total mass eroded and erosion rate are characterized during the internal erosion process. It is found that MICP treatment facilitates the reduction of erosion and hydraulic conductivity in sand – gravel mixture investigated in the current study. The optimum carbonate precipitation is seen in 0.6 M specimen and 7 days cured specimens. Carbonate precipitation increases the erosion resistance by absorbing and bridging the contacts of fine and coarse particles.**

Index Terms:- MICP, Rate of flow, Molar concentration, Downward erosion test.

I. INTRODUCTION

Internal erosion is the process which involves soil particles detachment and transport by seepage flow within the dam or levee, or its foundation. Backward erosion starts at the downstream side when the hydraulic gradient is high enough to cause movements of the particles and propagate to the upstream side. Concentrated leak initiated due to the hydraulic fracturing or poor compaction. Subsurface erosion in the form of piping has been one of the most prevalent causes of catastrophic failure of levees and earth dams. Earth dam is one of the most widely constructed hydraulic infrastructures around the world. The safety of earth dams has drawn increasing attentions from the public due to less predictable and more extreme weather conditions over recent years. One mode of failure is piping through embankment, which is initiated by internal erosion of soil particles within dam cores. Typically, the erosion process involves the transport of fine particles (e.g. sand) beyond critical hydraulic criteria. Therefore, it is necessary to develop efficient control strategies to mitigate the severity of internal erosion. Microbially induced calcite precipitation (MICP) is an emerging bio-mineralization technique, which has been studied extensively in the field of civil engineering. It involves the process of calcite precipitation via bacteria-induced ureolysis. The formed precipitation could cement particles at contact points, thereby reducing their susceptibility to seepage-induced erosion while still retaining relative high permeability. In this study, a series of rigid-wall column erosion tests were conducted to investigate the effect of MICP treatment on mitigation of internal erosion in an internally unstable sand-gravel mixture. Both untreated and MICP treated binary mixtures were subjected to downward seepage flow with incremental flow rates. Evolution of hydraulic conductivity and total erosion mass against different molar concentrations of solution were measured.

Most experimental research on the internal erosion process used homogeneous or mixed soils with one-dimensional flow in columns (Fleshman & Rice, 2014; Ouyang & Takahashi, 2016). Some sophisticated tests were also conducted recently as attempts to better represent the erosion process in real dams. For example, Correia dos Santos et al. (2015) constructed a column soil sample with three zones representing the upstream, core and downstream materials. Planès et al. (2016) constructed a scaled canal embankment, which was tested to failure by internal erosion in an indoor laboratory. Microbially induced carbonate precipitation (MICP) is an emerging bio-mineralisation technique, which has been extensively investigated for its applicability in geotechnical, environmental and energy engineering (Al Qabany & Soga, 2013; the calcite precipitation produced preferentially accumulates around particle–particle contacts (Al Qabany et al., 2012). Because of this preference of cementation at pore throat locations, large pores are kept relatively open so that the change in permeability is rather small, even though soil stiffness and strength are enhanced (Whiffin et al., 2007; Martinez et al., 2013; Dawoud et al., 2014). This is an attractive feature of MICP for internal erosion control. A study of MICP for internal erosion control in sand–clay mixtures has been performed by the authors (Jiang et al., 2016a).

In this study, the MICP technique was tested for internal erosion control in sand-gravel mixtures. A series of internal erosion tests are conducted using a rigid wall downward erosion test apparatus for untreated, 0.2M, 0.4M, 0.6M, 0.8M and 1M specimens. The tests are also conducted for 3 days and 7 days cured specimens. The flow rate of water is varied as low, medium and high flow. Hydraulic conductivity, total mass eroded and erosion rate are characterized during the internal erosion process.

II. MATERIALS USED

Testing materials

A. Tested soil. Core materials in embankment dams and levees are built using broadly graded soil to avoid seepage-induced internal erosion. In this study, locally collected sand and gravel were used as the sample medium. The gravel and sand were mixed at a ratio of 1:1 based on dry weight (i.e. sand content 50%). The binary mixture was categorized as gap-graded soil based on the criteria proposed by Lafleur et al. (1989). A standard Proctor compaction test gives the result that the binary mixture has a maximum dry density ($\gamma_{d,max}$) of 1.878g/cc and optimum water content (w_{opt}) of 14.48%.

Table. I Index properties of sand

Parameters	Value
Specific Gravity	2.61
Effective size, D10 (mm)	0.22
D30 (mm)	0.39
D60 (mm)	0.68
Uniformity coefficient, Cu	3.09
Coefficient of curvature, Cc	1.01
Gradation of sand	SP
Maximum density (g/cc)	1.718
Minimum density (g/cc)	1.461
Angle of internal friction (degree)	43^0

Table. II Index properties of gravel

Parameters	Value
Specific Gravity	2.82
Effective size, D10 (mm)	4.9
D30 (mm)	6.6
D60 (mm)	8.2
Uniformity coefficient, Cu	1.673
Coefficient of curvature, Cc	1.084
Gradation of sand	SP
Maximum density (g/cc)	1.601
Minimum density (g/cc)	1.32

Flakiness index	5.78%
Elongation index	62.5%

B. Bacteria and cementation solution. The bacteria Bacillus Subtilis strain JC3 was used in this study. Pure culture of Bacillus Subtilis was collected from the department of Agricultural Microbiology, College of Horticulture, Vellanikkara, Thrissur. Urea (NH2CONH2) and Calcium Chloride Dihydrate (CaCl2.2H2O) were used for the work. They are known as cementation reagent. Sufficient amount of cementation reagent is essential for the urea hydrolysis to take place effectively. Egg white and yolk were used as organic supplement after removing fat (1% by weight of soil). It contributes to the major source of nutrient for the growth of microbes.

The selected concentrations (0•2 M, 0•4 M, 0•6 M and 1•0 M) cover the range adopted in most previous studies that showed effective MICP treatment (Al Qabany & Soga, 2013; Montoya et al., 2013; DeJong et al., 2014).

III. EXPERIMENTAL PROGRAM

A rigid-wall column erosion test apparatus, which allowed independent control of the MICP treatment, was used to conduct the internal erosion tests in this study. A schematic diagram of the test apparatus is shown in Fig. 1. This apparatus consisted of a rigid-wall column chamber, an upper water tank, and a collection flask. The rigid-wall column chamber was composed of a hollow transparent plastic column with a height of 200 mm and inner diameter of 60 mm.

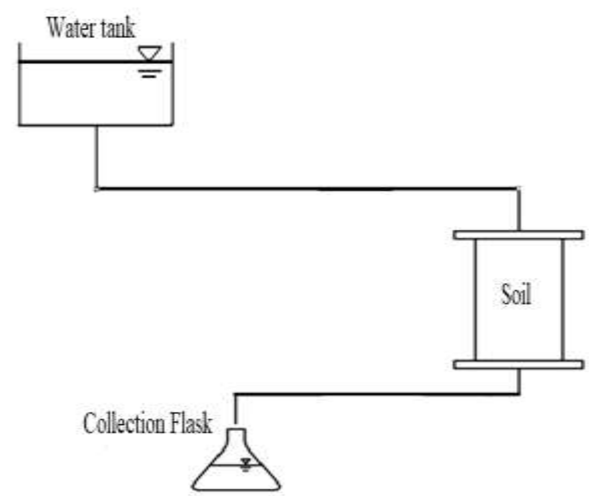

Fig. 1 Schematic diagram of the rigid-wall column erosion test apparatus

The sample is prepared by mixing the 1:1 ratio sand-gravel binary mixture with calcium chloride (CaCl2) and urea along with bacteria as liquid solution to optimum water content. The amount of calcium chloride solution and urea solution is taken in the ratio of 1:1 and bacteria is added by 1 ml for each10 ml of liquid solutions. The molarity of calcium chloride and urea solutions were varied ranging from 0.2M - 1 M such that to find out the optimum concentration of calcium chloride and urea for precipitation. Also samples (0.2M- 1M) were made for third and seventh day tests, the soil sample is cured by keeping the mixtures in air tight plastic covers.

The untreated and MICP treated specimens were subject to low, medium and high flow rates of water from the upper water tank. Low, medium and high flow rates are initiated by marking the tap with a marker (Fig. 2). Then the outflow containing sand particles through the outlet was collected. The collection time for determining hydraulic conductivity was 15 s and the overall test lasted for 10 minutes. The sand particles flowed through outlet were collected and oven dried to knew the total mass eroded for that particular flow rate. Photographs were taken immediately after the erosion test to facilitate visual checking of erosion severity.

Fig. 2 Photograph showing the markings of low, medium and high flow rates

Fig. 3 Rigid- wall column erosion test apparatus

IV. RESULTS AND DISCUSSIONS

The results of the internal erosion tests for gravel–sand mixtures were analysed by comparing the MICP treated and untreated samples according to the following three aspects: (a) visual observations; (b) total mass eroded for a particular flow; and (c) hydraulic conductivity.

A. Visual observations. In this study, photos were taken at every stage of the internal erosion for all samples (Fig. 5). For both untreated and MICP treated soils, the increased flow rate resulted in more noticeable fine particle erosion along the inner surface of the transparent wall. Erosion was also found to be less severe in the MICP treated samples than in the untreated samples under the same flow rate.

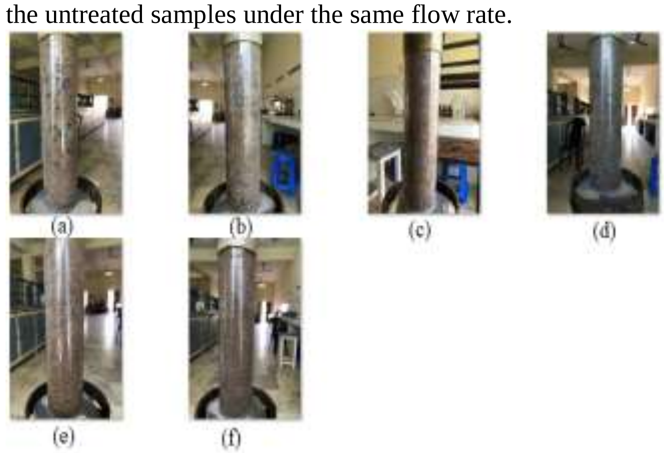

Fig. 4 Photographs of sand-gravel mixtures after internal erosion test: (a) untreated; (b) 0.2M; (c) 0.4M; (d) 0.6M; (e) 0.8M; (f) 1M

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B. Erosion characterisation. In this study, the weight of flushed sand particles was measured to determine cumulative erosion weight. Also the outflow is collected for 15 s to determine the hydraulic conductivity of the sample.

In the zeroeth day test, for the case of 0.2M treated sample there is an increase in hydraulic conductivity due to the lower precipitation of calcium carbonate in the sample (Fig. 6). As the molar concentration increases there is a decrease of hydraulic conductivity in 0.4M-1M. Also the total mass eroded is least for the 1.0 molar concentration added sample (Fig. 7). It is due to the high precipitation of calcium carbonate in the sample.

The graph showing the curves between molarity and hydraulic conductivity for 0th day is shown in Fig. 8. This represents the different rate of flows such as low, medium and high. From this graph, it is clearly understood that the optimum calcium source for lowering hydraulic conductivity and the total mass of sand eroded is 0.4M.

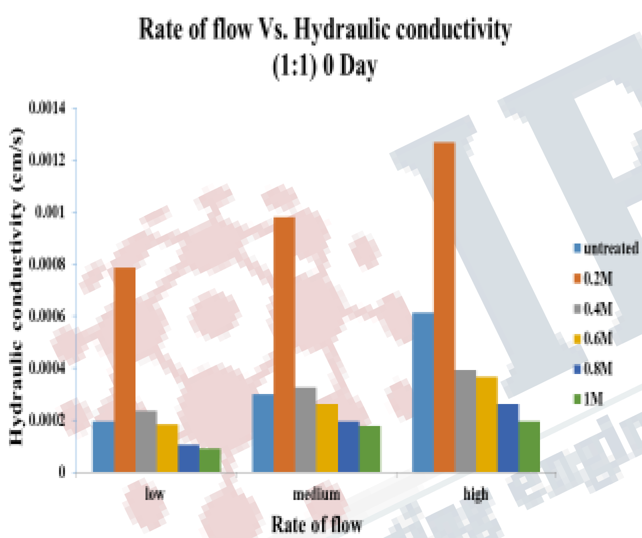

Fig. 5 Graph showing rate of flow vs. hydraulic conductivity for 0 da

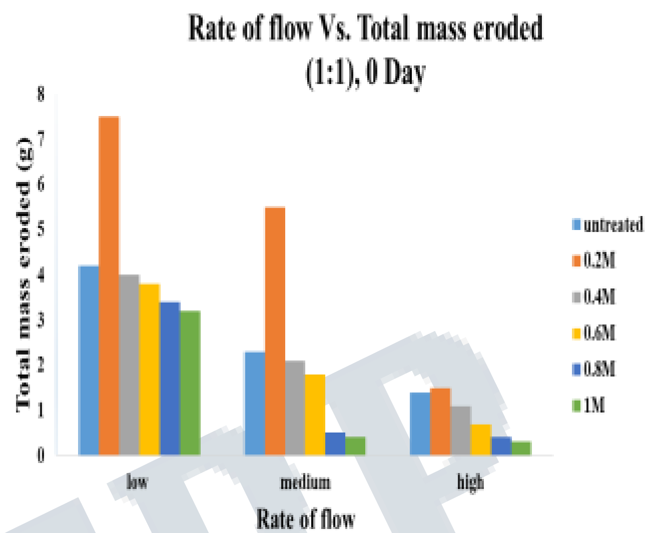

Fig.6 Graph showing rate of flow vs. total mass eroded for 0 day

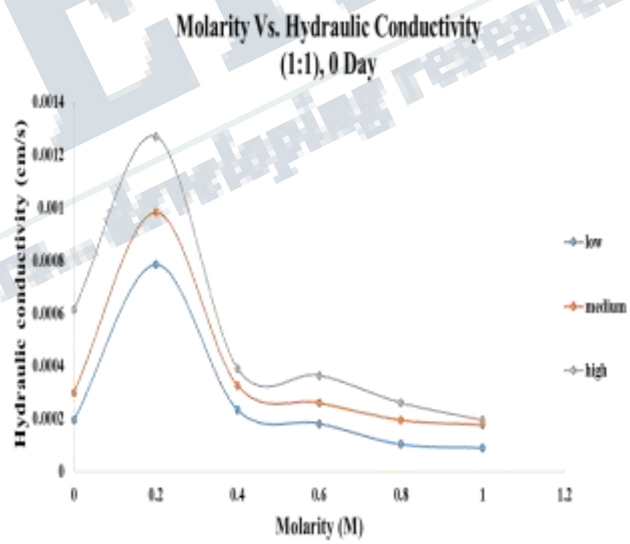

Fig. 7 Graph showing molarity vs. hydraulic conductivity for 0 day

In the third day test, there is an increasing pattern for hydraulic conductivity for 0.2M. The reason for that is same as that in the 0th day test. Then the hydraulic conductivity is decreasing as the molar concentration of the samples increases (Fig. 9). Also the total mass eroded is least for the 1M molar concentration added sample (Fig. 10). It is due to the high precipitation of calcium carbonate in the sample.

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The graph showing the curves between molarity and hydraulic conductivity for 3rd day is shown in Fig. 11. From this graph, it is clearly understood that the optimum calcium source for lowering hydraulic conductivity and the total mass of sand eroded is 1M.

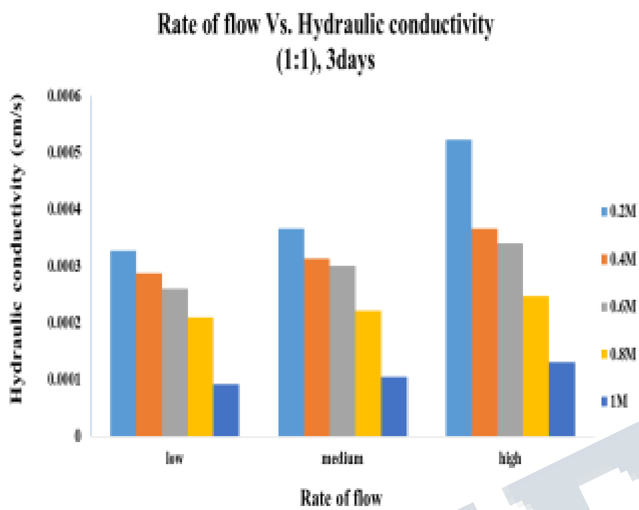

Fig. 8 Graph showing rate of flow vs. hydraulic conductivity for 3 days

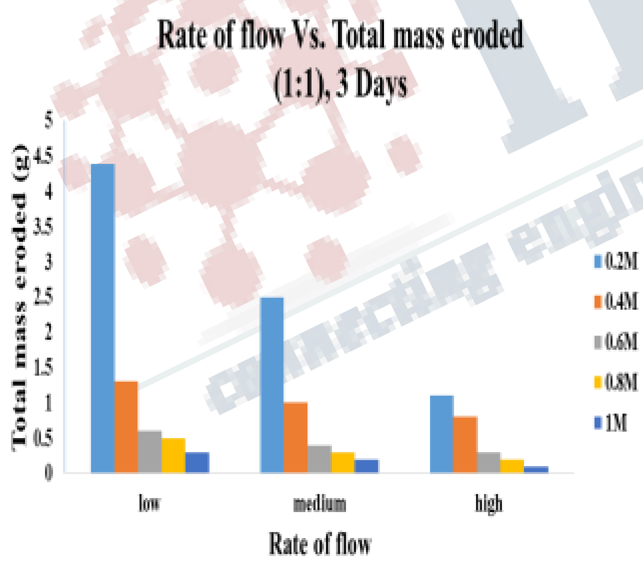

Fig. 9 Graph showing rate of flow vs. total mass eroded for 3 days

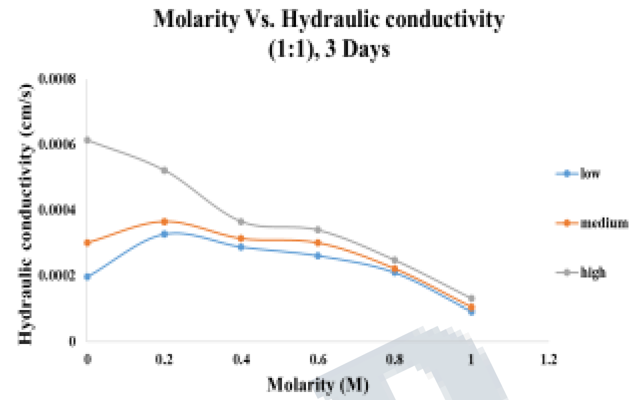

Fig. 10 Graph showing molarity vs. hydraulic conductivity for 3 days

In the seventh day test, there is an increasing pattern for hydraulic conductivity for 0.2M. The reason for that is same as that in the 0th day and 3rd day test. Then the hydraulic conductivity is decreasing as the molar concentrations of the samples increases (Fig. 12). Also the total mass eroded is least for the 1M molar concentration added sample (Fig. 13). It is due to the high precipitation of calcium carbonate in the sample.

The graph showing the curves between molarity and hydraulic conductivity for 3rd day is shown in Fig. 14. From this graph, it is clearly understood that the optimum calcium source for lowering hydraulic conductivity and the total mass of sand eroded is 1M.

Combining the zeroeth, third and seventh day test results it is clear that the hydraulic conductivity and total mass eroded is least for the seventh day test results. Therefore as the curing period increases the efficiency of MICP treatment to decrease the hydraulic conductivity and erosion increases.

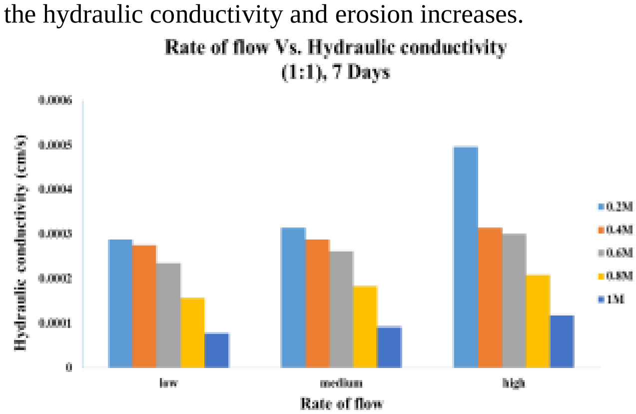

Fig. 11 Graph showing rate of flow vs. hydraulic conductivity for 7 days

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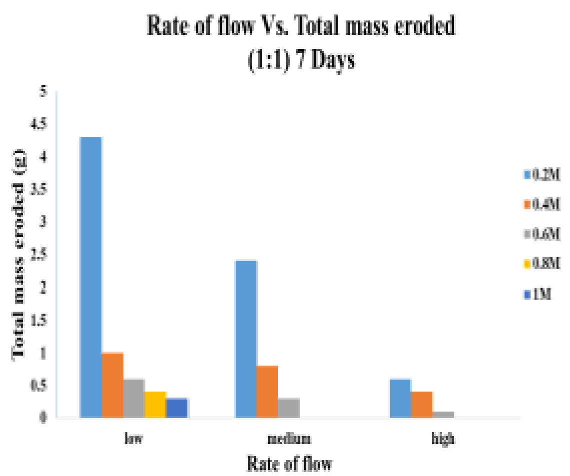

Fig. 12 Graph showing rate of flow vs. total mass eroded for 7 days

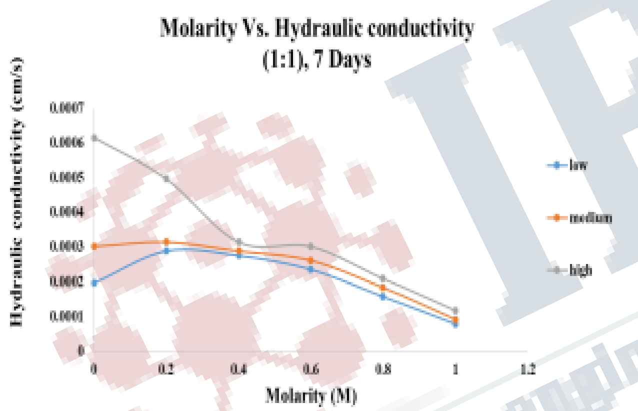

Fig.13 Graph showing molarity vs. hydraulic conductivity for 7 days

CONCLUSION

- MICP treatment contributes to a reduction in the cumulative erosion weight and hydraulic conductivity relative to untreated soil.
- A cementation concentration higher than 0.4M can bring down the erosion to a negligible level.
- The average calcium carbonate precipitation content increases steadily with increasing cementation concentration.
- More calcite precipitation corresponds to less erosion weight. The formation of clusters of cemented sand particles is fundamentally responsible for the reduction in soil erosion.

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