Behaviour of Stabilized Soils under Repeated Traffic Loading: A Review and Future Research Directions

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Abstract: Resilient modulus (M_R) is the critical input parameter for the characterization of pavement geo-materials subjected to repeated traffic loading. The effectiveness of a material in stabilizing soil for the subgrade layer of pavement is usually assessed by M_R estimated from quasi-static tests (California bearing ratio and unconfined compression strength), but these tests are not the accurate representation of repeated traffic loading, and hence the M_R must be determined through laboratory cyclic triaxial test. This review examined more than 35 research papers published over the period 1995 to 2019 and identified 15 stabilizers that have been tested for soil stabilization under cyclic tri-axial loading. The analysis of these articles highlights three different categories of stabilizers: first, waste materials such as fly ash, cement kiln dust, oil shale ash ground granulated blast furnace slag, dolime, bottom ash and lignin, second, chemical stabilizers such as lime, cement, lignosulfonate, sodium alginate bio-polymer and an ionic soil stabilizer and third, fibres such as polypropylene and lignin. The soils subjected to the test were organic clay and inorganic soils such as clay, sand, gravel containing soil and black cotton soil. The present paper discusses the effect of confining stress, cyclic deviator stress, number of load applications, curing period and dosage of the stabilizer on the M_R of the stabilized soils. The analyses of these articles help understand the importance of cyclic triaxial test for proper characterization of stabilized soils for use in pavement construction. The fact that only a limited number of stabilizers for the soil have been studied so far, this review identifies a scope of determining the M_R of materials that are potential soil stabilizers for future research.

Keywords: Resilient modulus, Cyclic triaxial test, Soil stabilization.

1 Introduction

In a roadway pavement, the subgrade layer provides the supports to the overlying layers of bituminous concrete and granular material. Henceforth, the subgrade must possess adequate stiffness under repeated traffic loading. Soils stabilization is a well-known technique for improving the engineering properties of soils. Availability of different type of stabilizers makes the selection of the right stabilizer a critical task. The efficacy of soil stabilizers for use in pavements must be assessed under repeated loading and should not solely be determined based on results obtained from static loading test results. Seed et al. (1955) were the first to introduce the concept of resilient modulus (M_R) for measuring the stiffness of a material under repeated traffic loading. M_R is the chief structural response parameter for characterizing the behaviour of different pavement layers under repeated traffic loading. Major pavement design guides (AASHTO 2015; Austroads 2018; IRC 2018) suggest the determination of M_R through laboratory repeated load triaxial test. Unfortunately, due to expensive equipment cost and a cumbersome procedure, other mechanical properties such as California bearing ratio (CBR) has been co-related with the M_R. However, these correlations may not be the true representative of the M_R due to the quasi-static property of CBR tests. Also, the stress dependence of M_R is not incorporated in these correlations.

The present review discusses the evolution of the concept of M_R in pavement design guides and discusses various factors affecting the M_R of subgrade soils, such as the effect of applied stresses, moisture content of the soil, curing period and density of soil. Divided into three sections, the paper reviews M_R of soils stabilized with waste materials, chemical stabilizers and fibres. The classification of soils reviewed in this study is denoted in parenthesis by the Unified Soil Classification System.

2 Evolution of the Concept of Resilient Modulus

The 1986 American Association of State Highway and Transportation Officials (AASHTO) pavement design guide employed the M_R to assign layer coefficients to characterize granular materials for the sub-base and base, and subgrade soils. In 1982, AASHTO T274-82 was developed for determining the M_R but was later retracted by the AASHTO material committee. In 1991, AASHTO approved an interim method of M_R testing (AASHTO T 292-1991) and was later modified to AASHTO T 294-1992. Following this SHRP testing protocol, P46 was developed, and it was further modified and developed into AASHTO standard T307-99. AASHTO T 307-99 is currently the standard test adopted by AASHTO for determining the M_R of pavement geomaterials in the laboratory. IRC 37 (2018) states that the M_R shall be determined as per AASHTO T 307-99 for the design of flexible pavements in India. AASHTO T 307-99 procedure states that the waveform of the loading should have 0.1 seconds as the loading time, followed by 0.9 seconds as the rest time. Moreover, it should be applied at each of the 15 stress states with 500-1000 cycles of loading for the conditioning of the sample.

3 The behaviour of Stabilized Soils under Repeated Loading

The behaviour of stabilized soils under dynamic loading needs to be assessed for its use in the subgrade layer of the pavement. An extensive review of the literature shows that limited materials have been studied for soil stabilization under dynamic loading. The literature related to the dynamic behaviour of soils stabilized with (i) waste materials, (ii) chemical stabilizers and (iii) fibre was reviewed in the following sections.

3.1 Soils stabilized with waste materials

Fly ash is the predominant waste material that has been used to stabilize inorganic & organic soils and tested under repeated loading. The majority of the work has been performed on self-cementing fly ash class C, whereas a less number of studies have used class F fly ash. Other waste materials such as cement kiln dust (also referred as lime kiln dust), ground granulated blast furnace slag (GGBFS), municipal solid waste fly ash and bottom ash, oil shale ash, bottom ash has been used to stabilize inorganic soils. Dolime, waste from the lime industry, has been used to stabilize black cotton soil and fly ash independently. Lignosulfonate, a by-product from the timber industry and lignin, a processed waste by-product from the paper manufacturing industry, has been used to stabilize a silty soil (ML).

Soils stabilized by Fly ash. Trzebiatowski et al. (2004) added fly ash (class C) (10%) to five soils (CL, SC & GC) and determined their $M_{R.}$ The laboratory-made samples were cured for seven days and prepared at a moisture content of 5% wet of optimum moisture content (OMC). The fly ash stabilized specimens obtained from the field were cured for 7 & 28 days. The authors reported an increase in M_R with fly ash stabilization and increase in curing period. The average M_R increased from near zero to 21 MPa. A decrease in M_R was reported with an increase in moisture content. Also, an increase in M_R with an increase in cyclic deviator stress was reported for seven days cured samples, whereas the opposite trend was reported for 28 days cured samples. Bin-Shafique et al. (2004) determined the efficiency of fly ash stabilization for different plasticity clayey soils (CL & ML-CL). The M_R was tested at a confining pressure of 21 kPa after 2-hour delay in mixing time. The authors reported increased M_R with fly ash stabilization. A decrease in M_R was reported with an increase in cyclic deviator stress.

Edil et al. (2006) stabilized one organic soil and six inorganic soils (OH, CL & CH) with four fly ash (class C, class F and off-specification) and determined their M_R at OMC, OMC+7% moisture and at very wet condition (OMC + 9 to 18% moisture) after seven days curing. The authors reported increased M_R (range 0.8 to 2.5 times at OMC condition) with fly ash stabilization. Also, it was reported that higher M_R was reported for fly ashes with calcium oxide content = 10% and calcium oxide / Silica oxide content = 0.5-0.8. The authors reported a decrease in M_R with an increase in cyclic deviator stress, water content and organic content. Also, an increase in M_R was observed with increase in confining pressure and fly ash percentage. The authors reported a better gain in M_R for lower plasticity soils. Presence of organic matter inhibited the development of stiffness in stabilized samples.

Li et al. (1999) added fly ash (class C) (10% & 12%) to a clay soil (CL) and the M_R tests were performed on samples cured for 14 days. The authors reported an increase in M_R with fly ash stabilization for both laboratory and field mixtures.

Solanki et al. (2009) used fly ash (class C) (5%, 10% & 15%) to stabilize a silty-clay soil (ML-CL) and compared the effectiveness of the stabilizer with lime and cement kiln dust. Solanki et al. (2010) further compared the behaviour for four soils (CH, CL & ML-CL). Singh et al. (2010) used fly ash (class C) (16%) to stabilize clay soil (CL) and compared the effectiveness of the stabilizer with lime. Hossain et al. (2013) compared the M_R of fly ash (class C) (5%, 10% & 15%), lime and cement kiln dust for four soils (CL, ML-CL & CH). The authors reported a decrease in M_R with an increase in cyclic deviator stress an increase in M_R with an increase in confining pressure and additive percentage. Lime and cement kiln dust provided the highest M_R for CL soil whereas fly ash (class C) provided the highest M_R for ML-CL soil. The octahedral model performed better than the other selected models.

Pinilla et al. (2011) used fly ash (class C) (15% & 16%) to stabilize three clay soils (CL & ML), and their M_R was determined after curing the samples for 1, 3, 7, 14 & 28 days. The authors reported a decrease in M_R with an increase in cyclic deviator stress and increase in M_R with an increase in confining pressure and additive percentage. The average increase in the M_R was reported to be in the range of 583% to 917%.

Tastan et al. (2011) stabilized organic soils (PT, OL, OL-OH & ML) with four fly ash (class C & class F) in the range of 20% to 30%, and determined their M_R at OMC and very wet condition after seven days curing. The authors reported higher M_R for fly ashes with calcium oxide content = 10% and calcium oxide / silica oxide content = 0.5-0.8. The authors reported a decrease in M_R with an increase in cyclic deviator stress, water content and organic content. Also, an increase in M_R was observed with increase in confining pressure and fly ash percentage. The authors highlighted the fact that loss on ignition, pH and fineness of fly ash did not affect the M_R of soil.

Kang et al. (2014) used fly ash (class C) (10%, 15% & 20%) to stabilized two clay soils (CL & CH). The M_R was tested after 1, 7, 14 & 28 days curing. The authors reported a decrease in M_R with an increase in cyclic deviator to stress an increase in M_R with an increase in confining pressure, curing period and additive percentage. The results were compared with soils stabilized with lime kiln dust where fly ash (class C) performed better than lime kiln dust.

Orakoglu et al. (2017) used fly ash (class F) (4% & 8%) to stabilize a clay soil (CL). The raw soil and fly ash-soil mixtures were further reinforced with lignin fibre. The effect of freeze and thaw on raw and stabilized samples was evaluated. M_R tests were performed after fifteen freeze-thaw cycles. The samples were frozen at $-20^{O}C$ and thawed at $20^{O}C$. The M_R increased with increase in confining pressure for all the specimens. Highest M_R was achieved for soil stabilized with 4% fly ash. Freeze and thaw cycles decreased the M_R of raw soil. The decrease in M_R of raw soils was approximately 49%, whereas the M_R of fly ash-soil mixtures showed a negligible decrease.

Rosa et al. (2017) stabilized an organic soil (OH) with three fly ashes (class C) and determined their M_R tested on samples cured for seven days. The authors reported a decrease in M_R with an increase in cyclic deviator stress and moisture content and an increase in M_R with an increase in confining pressure, freeze and thaw cycles and compacted density.

Choudhary et al. (2018) added fly ash (class C) (20%, 40%, 60%, 80% & 100%) to a black cotton soil (CH) and the M_R was tested on samples cured for 0 and 28 days. The authors reported that the M_R of soil fly ash mixes increases with increase in fly ash content up to 40% and decreases after that for 28 days cured samples except for 100% fly ash. Regarding samples cured for zero-days, it was reported that the M_R decreases with increase in fly ash content due to the less pozzolanic reaction. The authors also stated that the permanent strain decreases with increase in curing period and fly ash content up to 40% content, except for 100% fly ash content.

Soils stabilized by GGBFS. Puppala et al. (2003) stabilized a clay soil (CL) with GGBFS (20%) and compared its performance with soil stabilized with sulphate resistant cement (8%) and a mixture of fly ash (class F) (15%) and cement (5%). Chavva et al. (2005) further compared the performance of GGBFS (20%) with a mixture of polypropylene fibre (0.15%) and lime (8%) to treat a clay soil (CL). The samples were cured for seven days before testing. The authors reported an increase in M_R with an increase in confining pressure but a decrease in M_R with an increase in deviator stress. Based on the M_R obtained in the laboratory, the authors reported that cement was the most effective in increasing the M_R of the soil, followed by cement fly ash mix, GGBFS and lime-fibre mixture.

Soils stabilized by cement kiln dust. Solanki et al. (2007) used cement kiln dust (5% & 15%), to stabilize a silty-clay soil (ML-CL) and compared the effectiveness of the stabilizer with fly ash (class C) and lime. Co-relation of M_R with octahedral stress state model, unconfined compressive strength &California bearing ratio was successfully developed. Solanki et al. (2010) further compared the behaviour for four soil types (CH, CL & ML-CL). Hossain et al. (2013) compared the M_R of lime, fly ash (class C) and cement kiln dust for four soils (CL, ML-CL & CH). The M_R was tested after the 28-day curing. The authors reported a decrease in M_R with an increase in cyclic deviator stress and an increase in M_R with an increase in confining pressure and additive percentage. Lime and cement kiln dust provided the highest M_R for CL soil whereas fly ash (class C) provided the highest M_R for ML-CL soil.

Pinilla et al. (2011) used cement kiln dust (12% & 14%) to stabilize two sandy soils (SC & SM), and their M_R was determined after curing the samples for 1, 3, 7, 14 & 28 days. The authors reported a decrease in M_R with an increase in cyclic deviator stress and increase in M_R with an increase in confining pressure and additive percentage. The average increase in the M_R was reported to be in the range of 1973% to 4519%. Kang et al. (2014) used lime kiln dust (4% & 8%), to stabilized two clay soils (CL & CH) and compared the effectiveness of the stabilizer with fly ash (class C) The M_R was tested after 1, 7, 14 & 28 days curing. The authors reported a decrease in M_R with an increase in cyclic deviator to stress an increase in M_R with an increase in confining pressure, curing period and additive percentage. The results were compared with soils stabilized with fly ash (class C), where lime kiln dust performed worse than fly ash.

Soils stabilized by Municipal Solid Waste Ash. Vizcarra et al. (2013) used Municipal solid waste fly ash and bottom ash (20% & 40%) to stabilize a clay soil (CL). The M_R results were determined after 7 & 28 days curing. The authors reported a decrease in M_R with an increase in cyclic deviator stress, water content and number of load cycles. Also, an increase in M_R with an increase in confining pressure and curing time was reported.

Soils stabilized by Oil Shale Ash. Wei et al. (2018) determined the M_R of a mixture of Oil shale ash (20%), class C fly ash (40%) and sandy clay soil (SC). The samples were cured for three days and subjected to freeze and thaw cycles. The authors reported a decrease in M_R with freezing and thawing and increased in cyclic deviator stress. Also, an increase in M_R with an increase in confining pressure and curing time was reported.

Soils stabilized by Bottom Ash. Asefzadeh et al. (2018) used Municipal solid waste fly ash and bottom ash (20% & 40%) to stabilize a clay soil (CL). The M_R was determined for samples prepared at three moisture contents (OMC-2, OMC, OMC+2%) and cured for one day. The optimum bottom ash content was determined as 25%. The authors reported a decrease in M_R with an increase in cyclic deviator stress and moisture content. Also, an increase in M_R with an increase in confining pressure and curing time was reported.

Soil stabilized with Dolime. Patel and Shahu (2018) prepared two mixtures: (1) a mixture of dolime (9%) and black cotton soil (CH) and (2) a mixture of dolime (10%) and fly ash (class C) for use as the sub-base materials in pavement construction. The M_R was determined on samples cured for 0, 7, 14 & 28 days. The authors reported an increase in M_R and decreased in permanent deformation with an increase in the curing period, confining pressure and cyclic deviator stress. The M_R of the dolime-soil mix was reported to be higher than the M_R of fly ash-dolime mixture.

Soil stabilized with Lignin Zhang et al. (2018) compared the performance of lignin (2%, 5% & 8%) with quicklime (2%, 5%, 8%, 12% & 15%) in stabilizing a silty soil (ML). The samples for M_R tests were prepared at 94% & 96% of the maximum dry density and were tested after 1, 7 & 28 days of curing. The authors reported a decrease in M_R with an increase in cyclic deviator stress and curing period and an increase in M_R with an increase in confining pressure and compacted density. The study showed that the optimum dosage of lignin was 12% and M_R obtained at this dosage was higher than the M_R of soil stabilized by 8% quicklime.

3.2 Soils stabilized with chemical stabilizers

Predominantly, lime and cement stabilized clay soils, and sand-fly ash mixtures have been tested under repeated loading. Expansive soils have been stabilized with lime. Soils have been stabilized with mixtures of cement and fly ash (class F) and lime and polypropylene fibre. An ionic soil stabilizer was used to stabilize two high plastic soils (CH). Sodium-alginate bio-polymer has been used to stabilize plastic soils.

Puppala et al. (1996) stabilized clay soil (CL) with lime (4%) and reported an increase of 20% to 50% in the M_R of the soil. The cyclic triaxial test to determine the M_R was performed at five different moisture contents near the OMC (OMC-4% to OMC +4%). The authors reported an increase in M_R with an increase in confining pressure and cyclic deviator stress. The M_R decreased with increase in moisture content.

Achampong et al. (1997) determined the M_R of two clay soils (CL & CH) stabilized by lime (2%, 4% & 6%), The treated samples were prepared at three moisture contents (OMC-2%, OMC & OMC+2%) at two curing periods (7 & 28 days). The authors reported an increase in M_R with an increase in the chemical stabilizer content and curing period. A decrease in M_R with an increase in moisture content and cyclic deviator stress was reported by the authors. Paired student t-test result shows a significant effect of curing period and soil type (M_R for CL soil was greater than that for CH soil. The results were compared with soils stabilized by cement (2% & 4%), and the cement stabilized soils showed a better improvement in M_R than lime stabilized soils.

The M_R testing was further extended for field application. Yusuf et al. (2001) determined the M_R of soil samples obtained from a stretch of road. A total of 4 samples stabilized with lime (5, 6, 6 & 4% lime for sample 1, 2, 3 & 4 respectively) were subjected to repeated cyclic triaxial testing. The samples were tested in dry and 24-hour soaked condition after seven days curing. The M_R obtained in the field from falling weight deflectometer tests co-related well with the laboratory cyclic triaxial test results. The authors reported an increase in M_R with lime treatment but reduced M_R for samples subjected to soaking before testing.

Puppala et al. (2003) added sulphate resistant cement (8%) and fly ash (class F) (15%) mixed with cement (5%) mixture to a clay soil (CL). The samples were cured for seven days. The authors reported a decrease in M_R with an increase in cyclic deviator stress and an increase in M_R with an increase in confining pressure. The results were compared with the soil stabilized with GGBFS (20%). The performance order of the stabilizers based on the M_R reported is cement >cement + fly ash > GGBFS. Chavva et al. (2005) further compared the performance of cement and fly ash cement mix with a mixture of polypropylene fibre (0.15%) and lime (8%), and reported that the lime-fibre mixture was the least effective in increasing the M_R of the soil.

Arora and Aydilek (2005) stabilized a mixture of 40% fly ash (class F) and 60 % sandy soil (SP) with lime (7%). The samples were cured for 7-day. The authors reported an increase in M_R with an increase in lime content. Also, an increase in M_R with an increase in bulk stress was reported. The results were compared with soils stabilized by cement (1%, 2%, 4%, 5% & 7%) and the cement stabilized soils showed a better improvement in M_R than lime stabilized soils.

Mohammad and Saadeh (2008) used lime (10%) to stabilize clay soil (CL). The M_R results were determined after 28-days curing. The authors reported a decrease in M_R for a lime-soil mix with an increase in cyclic deviator stress. Also, an increase in M_R with an increase in confining pressure was reported. The results were compared with soil stabilized by cement (8%) and the cement stabilized soil showed a better improvement in M_R than lime stabilized soil. The authors reported an increase in M_R for a cement-soil mix with an increase in cyclic deviator stress. Also, an increase in M_R with an increase in confining pressure was reported.

Khoury et al. (2013) added lime (6%) to high plastic clay (CH) and prepared samples at OMC. The samples were subjected to wetting and drying, and the effect of post compaction moisture changes on the M_R of soil was evaluated. Qian et al. (2014) added 8% lime to a high plastic clay (CH) and tested at different moisture content. The authors reported that the M_R decreases with increase in moisture content and cyclic deviator stress. Also, the M_R increases with increase in confining pressure and compacted density.

Yuan et al. (2019) added lime (3%, 6% & 9%) to a high plastic soil (CH). The cyclic triaxial test to determine the M_R was performed on samples prepared at 91%, 93% & 95% of maximum dry density. Samples were prepared at three moisture contents (OMC-3%, OMC & OMC+3%). The samples were cured for seven days. The authors reported a decrease in M_R with an increase in moisture and cyclic deviator stress and an increase in M_R with an increase in confining pressure, density and additive content, where cement performed slightly better than lime. The results were compared with soils stabilized by cement (3%, 6% & 9%) and the cement stabilized soils showed a better improvement in M_R than lime stabilized soils.

Soils were stabilized with a combination of cement and lime. Sirivitmaitrie et al. (2011) used a combination of cement (4%) and lime (4%) to stabilize three high plastic clays (CH) and compared the results with lime (4%) treated soils. Abu-Farsakh et al. (2015) added lime, cement and a combination of lime and cement in 1:1 ratio (max. dosage 12%) to stabilize five soils (CL & CH). The M_R was determined at three moisture contents on samples cured for 7 and 28 days. The authors reported a decrease in M_R with an increase in cyclic deviator stress and an increase in M_R with an increase in confining pressure and compacted density. The authores reported an increase in M_R and a decrease in permanent deformation with an increase in water/cement ratio and curing period. Also the authors reported that higher plasticity soils required higher stabilizer content to achieve comparable $M_{R.}$

Solanki et al. (2009) used lime (3%, 6% & 9%), to stabilize a silty-clay soil (ML-CL) and compared the effectiveness of the stabilizer with fly ash (class C) and cement kiln dust. Solanki et al. (2010) further compared the behaviour for four soil types (CH, CL & ML-CL) on stabilization with lime (3%, 6% & 9%), fly ash (class C) (5%, 10% & 15%), cement kiln dust (5%, 10% & 15%). The M_R was tested after the 28-day curing. Singh et al. (2010) used lime (5%) to stabilize a clay soil (CL) and compared the effectiveness of the stabilizer with fly ash (class C). Hossain et al. (2013) compared the M_R of lime, fly ash (class C) and cement kiln dust for four soils (CL, ML-CL & CH). The authors reported a decrease in M_R with an increase in cyclic deviator stress an increase in M_R with an increase in confining pressure and additive percentage. Lime and cement kiln dust provided the highest M_R for CL soil whereas fly ash (class C) provided the highest M_R for ML-CL soil. The octahedral model performed better than the other selected models.

Expansive soils stabilized by lime Elkady (2015) added lime (2%, 4% & 6%) to an expansive clay and M_R of 7 and 28 days cured samples were determined. The percentage increases in M_R ranged from 360% to 370% for samples cured for 28 days. The optimum content of lime was 4%. Mamatha and Dinesh (2017) added lime (2.25%, 2.5%, 2.75% & 3%) to a black cotton soil (CH). The M_R was tested after curing the samples for 7, 14 & 28 days. The samples were compacted at OMC, wet of OMC and dry of OMC. Samples were compacted at standard and modified effort and tested under soaked and un-soaked conditions. Bhuvneshwari et al. (2019) lime (2%, 4%, 6% & 8%) to stabilize an expansive clay (CH). The M_R was tested on samples cured for 0, 3 & 28 days and two-day soaking. The authors reported a decrease in M_R with an increase in cyclic deviator stress, compacted density and moisture content and an increase in M_R with an increase in confining pressure, compacted density and curing period. The permanent strain increases with increase in loading cycles and decreases with increase in lime content and curing period. Soaking increases M_R and decreases permanent strain.

Soil stabilized with Lignosulfonate Chen et al. (2014) added Lignosulfonate (2%) to a clay soil (CL) and determined its M_R after curing the samples for seven days. The authors observed an increase in MR with lignosulfonate stabilization. The authors reported a decrease in M_R with an increase in cyclic deviator stress and number of load cycles. Also, an increase in M_R with an increase in confining pressure was reported.

Soil stabilized with Ionic Soil stabilizer (ISS) He et al. (2018) added Ionic Soil stabilizer (ISS) in three dosages as reported in table 1, to two clay soils (CH). The M_R was determined for samples cured for 7 & 28 days. Dosage 1 was found as the optimum content. The authors reported a decrease in M_R with an increase in cyclic deviator stress and curing period. Also, an increase in M_R with an increase in confining pressure was reported.

Table 1: Three liquid stabilizer dosage designs for soil treatment

ISS content	First ratio	Second ratio	Third ratio
Chemical Concentrate (ml)	5	5	10
Surfactant (g)	0.057	0.057	0.114
Water (gallon)	2	2	1

Soil stabilized with Sodium-alginate Bio-polymer Arab et al. (2019) added Sodium-alginate Bio-polymer to a clay soil (CH) (2%, 4% & 6%) and a silty soil (ML) (1%, 2% & 4%). The M_R was determined for samples cured for 0, 4, 7, 14 & 28 days. The samples were prepared using wet and dry mixing method used. The authors reported that with an increase in cyclic deviator stress the M_R for the stabilized silty soil (ML) decreases while the stabilized clay soil (CH) show an opposite trend. The authors also reported an increase in the M_R with an increase in confining pressure and curing period. The study showed that the optimum dosage of sodium alginate was 1% (for ML soil) and 2% (for CH soil) and the wet mixing method gave higher M_R results.

3.3 Soils reinforcement with fibres

Limited studies have accessed the performance of fibre-reinforced soils under repeated loading. The polypropylene fibre, coir fibre and lignin fibre have been tested under repeated loading. Additionally, the effect of freeze and thaw was also evaluated on the M_R of the stabilized soils. In general, fibre reinforcement increases the M_R and decreases the permanent strain. Refeai and Al-Suhaibani (1998) reported that the M_R increased up to the optimum content of fibre (0.2% to 0.4%). Hojjati and Sarkar (2019) reported an increase in M_R of silty clay (ML-CL) on reinforcement with polypropylene fibre (length 20 mm, dosage 0.5%).On the contrary, AI Wahab and Heckel (1995) reported a decrease in M_R with an increase in fibre content for clay soil (CL) reinforced with polypropylene fibre. However, the authors' findings corresponding to permanent strain behaviour of the reinforced soil was in coherence with the finding of other researchers. Reduction in permanent strain would reduce the depth of rutting in fibre reinforced soils. AI Wahab and Heckel (1995) observed an increase in total load cycles to failure for fibre reinforced soil. This observation confirms higher traffic load-carrying capacity of fibre-reinforced soils. In general, fibre reinforced soils exhibit strain hardening behaviour on increase in confining pressure. Contradictory behaviour of reinforced soils was reported on an increase in the cyclic deviator stress.

Kumar and Singh (2008) used polypropylene fibre (0.2%& 0.3%) to reinforce fly ash (class F) and a mixture of 75% fly ash and 25% soil (SP). Chauhan et al. (2008) used polypropylene fibre (1%) to reinforce a mixture of fly ash (class F) (30%) and a sandy soil (SP) (70%). The authors of both the studies reported an increase in M_R with an increase in confining pressure but a decrease in M_R with an increase in deviator stress and several load cycles.

Chavva et al. (2005) used a mixture of polypropylene fibre (0.15%) and lime (8%) to treat clay soil (CL). The samples were cured for seven days before testing. The authors reported an increase in M_R with an increase in confining pressure but a decrease in M_R with an increase in deviator stress. The authors compared the performance of fibre lime mixture with cement, GGBFS (20%) and a mixture of cement (5%) and fly ash (15%). The authors reported that the lime-fibre mixture was the least effective in increasing the M_R of the soil.

Chauhan et al. (2008) compared the performance of polypropylene fibre (1%) with coir fibre (0.75%) and reported that the coir fibre performed better than polypropylene fibre. The authors reported an increase in M_R with an increase in confining pressure, but a decrease in M_R with an increase in deviator stress and several load cycles for coir fibre reinforced soil.

Orakoglu et al. (2017) used lignin fibre (0.25%, 0.5%, 0.75% & 1%) to reinforce clay soil (CL) and soil-fly ash (class F) (4% & 8%) mixtures. The effect of freeze and thaw cycles on raw and stabilized samples were evaluated. M_R tests were performed after fifteen freeze-thaw cycles. The samples were frozen at -20^{O}C and thawed at 20^{O}C. The M_R increased with increase in confining pressure for all the specimens. Highest M_R was achieved for soil stabilized with 4% fly ash. Fibre reinforcement slightly decreased the M_R of raw soils and fly ash stabilized soils. Freeze and thaw cycles decreased the M_R of raw soil. The decrease in M_R of raw soils was approximately 49% whereas the M_R of fly ash and lignin fibre-soil mixtures showed a negligible decrease of 6 to 10%. It is worthwhile to note that certain soil-fly ash-fibre mixtures showed higher M_R after being subjected to fifteen freeze and thaw cycles.

4 Conclusions

1. Cyclic triaxial test emerged as a critical and essential test to determine the behaviour of pavement geo-materials under repeated traffic loading. The present review shows that only a limited number of studies have studied the behaviour of stabilized soils subjected to repeated cyclic loading. Also, the majority of the studies performed were outside India.
2. Generally, an increase in the curing period and compacted density increases the $M_{R,}$ whereas increase in moisture content decrease the M_R of soils stabilized by any category of stabilizer. In general increase in confining pressure and cyclic deviator stress increases the M_R of stabilized soils for any category of the stabilizers. Few studies have shown that an increase in cyclic deviator stress decrease in the M_R of chemically stabilized soils.
3. Regarding soils stabilized with waste, mainly fly ash, has been extensively used in soil stabilization and testing under repeated loading. Ground granulated blast furnace slag, municipal solid waste fly ash and bottom ash, oil shale ash, bottom ash are other stabilizers, but limited studies have been performed with these materials. No study has undertaken the effect of moisture, curing, soaking, density and field stress together in a single study. The effects have not been analysed for organic soils. The effect of combination of these materials has not been assessed under repeated loading.
4. Lime and cement are effective in increasing the M_R and decreasing the permanent strain in weak subgrade soils. Lime has been added in a range of 2% to 10% whereas cement has been added in the range of 2% to 8%. The combined dosage of lime and cement has generally been adopted in the ratio of 2:1 and 1:1. In general, M_R increases with an increase in the dosage of lime or cement. Researchers have reported higher M_R values for cement stabilized soils than lime stabilized soils. Stabilization with a combination of cement and lime further enhanced the M_R of soils. New chemical stabilizers such as lignosulfonate, sodium-alginate biopolymer and an ionic soil stabilizer (ISS) have not been studied in detail.
5. The availability of limited number of studies on fibre reinforced soils gives a limited knowledge of the behaviour of fibre-soil composites under repeated loading. This hinders the application of fibre reinforced soils for pavement construction at a large scale. The effect of reinforcement of different types of natural and synthetic fibres other than polypropylene fibre has not been studied. The effect of variation of fibre dosage, fibre length, compacted density, compacted moisture, soaking and freeze and thaw for reinforcing soils of different plasticity has not been stud-

ied. Also, the performance of fibre-reinforced chemically and mechanically stabilized soils has not been evaluated in detail. Hence, much work needs to be performed in the field using fibre reinforced soil for their application in pavement.

5. Future Research Directions

Cyclic triaxial test is essential for the determination of $M_{R,}$ but due to the high cost and cumbersome procedure, the pavement designers adopt M_R co-related from quasi-static tests such as CBR. Their is a need to perform the tests that incorporate all the variables influencing the M_R of soils. The complete study should address the effect of soaking of soil specimens as well. There is a need to conduct a national programme where samples from the field, obtained across India, need to be tested under repeated loading. Also, not all cyclic triaxial testing machines are upgraded and equipped to conducted repeated load triaxial tests and must be upgraded to obtain comparable results among different laboratories across India. Proper characterization of material through cyclic triaxial tests would lead to accurate pavement design and impart confidence in pavement designers to build better roads in future.

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