CHAPTER- III

MATERIALS, EXPERIMENTAL PROGRAM, METHODS AND TEST PROCEDURES

3.1 INTRODUCTION

The research aims to the reusability of the MSW fines collected from the Ramana site of Varanasi (India) for the geotechnical applications in the field. To consider it as a geomaterial and to recommend it in fields, it must go through various physicochemical as well as geotechnical tests. Moreover, to recommend the material in moderate to high seismic zones it is important to study its dynamic characteristics. One of the versatile equipment to stimulate dynamic loading at a large stain range in the laboratory is cyclic triaxial which can be stress or strain-controlled. The other laboratory equipment used to find the V_s (shear wave velocity) and shear modulus parameters of the material at a low strain range is the bender element (BE).

This chapter includes the source of collected wastes, reinforcing material used, the segregation process, detailed testing programs, and equipment used.

3.2 SOURCE OF MATERIALS USED

3.2.1 MSW Fines

The MSW fines have been segregated from the waste collected from Site 1- Ramana site in Varanasi, Uttar Pradesh, India (25° 14' 38.52332" N, 83° 0' 17.83084"E). The

location of the site has been marked in the map shown in Figure 3.1. This was an unauthorized open dump site which has been banned in 2016. The site is near the NTPC (National Thermal Power Corporation Limited) Ramana-Varanasi sewage treatment plant and around 5-6 km from the IIT(BHU) Varanasi campus and located near the drainage passage of the river Ganga. The segregation process of the fines (soil-like material) from the waste has been discussed in detail in the following section of this chapter.

3.2.2 Fibers

The fibers were a part of the waste that was collected from the Site 2- Karsada WtE plant in Varanasi, Uttar Pradesh, India, (25° 12' 54.61592"N, 82° 55' 10.71875"E) shown in Figure 3.1. The waste-to-energy plant (WtE) was set up by National Thermal Power Corporation (NTPC) in 2019 with an installed capacity of 200 kW. It is a thermal Gasification based pilot scale 24 tons per day Waste to Energy plant. The collected sample was the 4 mm rejected sample from which the fibers were segregated, the process has been discussed later in the chapter.

3.3 TESTING PROGRAM

3.3.1 Sample Collection and Segregation of Waste

The samples were collected from the two sites as described in the previous section. The materials as per the requirement of the study have been extracted or segregated from the collected waste. The MSW fines have been segregated from the Site 1- Ramana open dump site waste and the fibers were extracted from the Site 2- Karsada WtE plant waste. The collection and segregation process for the individual material has been discussed below.

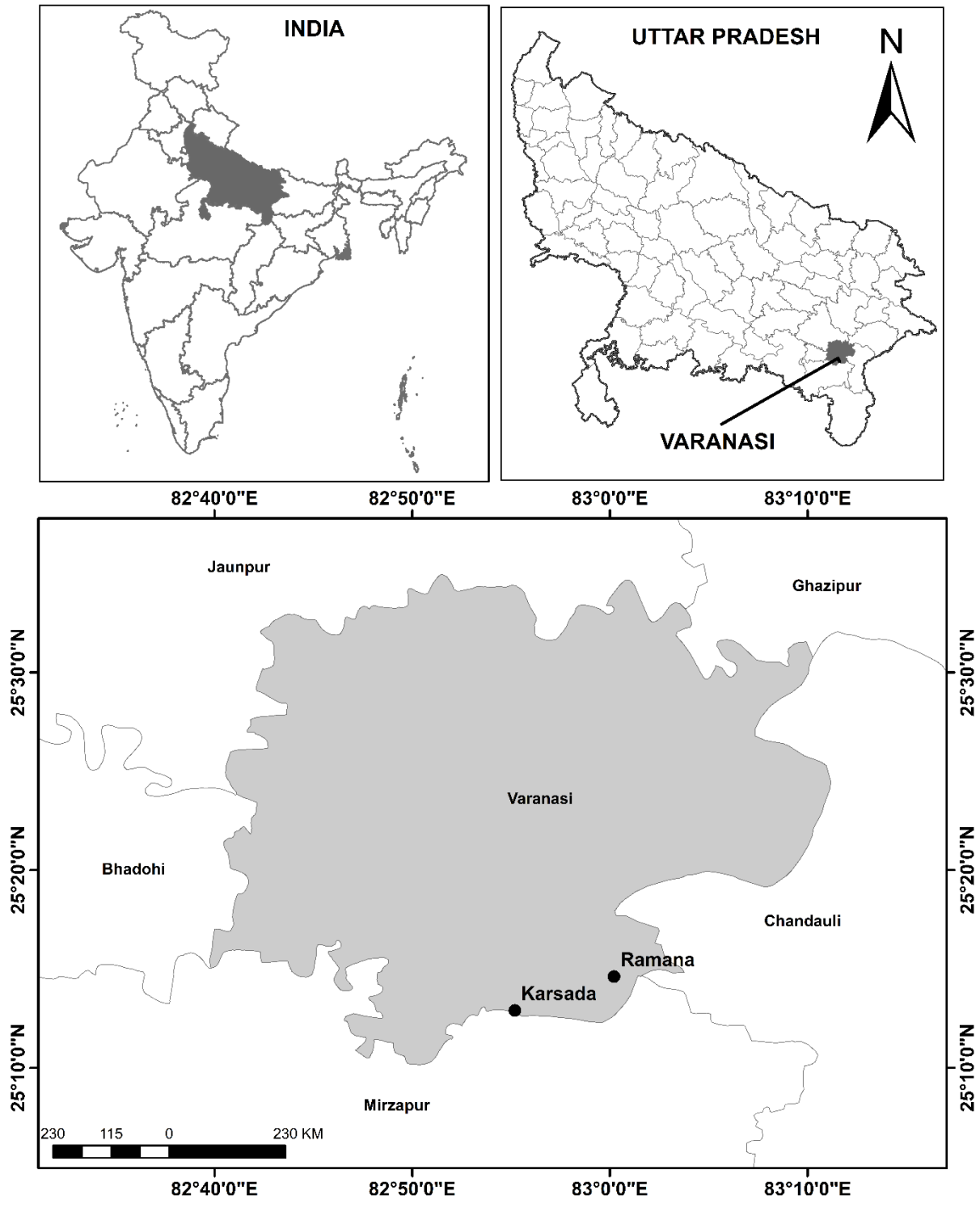


Figure 3.1 Location map of the sample collection sites

3.3.1.1 MSW Fines

The MSW samples from the site-1 Ramana open dump were collected manually from about 4 to 5 points on-site at an average depth of 1 m from the surface. More than 100 kg of the unsegregated sample was collected and sealed in the bags. Further, the waste was dried, segregated, and processed in the laboratory. The waste was segregated by using different Indian Standard (IS) sieves, i.e., 45, 26.5, 8, and 4.75 mm. Figure 3.2 shows the five-step segregation process. Most of the plastic and fibers retained above 26.5 mm sieve and only the fine fractions, i.e., MSW fines (i.e., below 4.75 mm size) were considered for the study. It was observed that about 50%–60% of the collected waste was categorized under MSW fines.

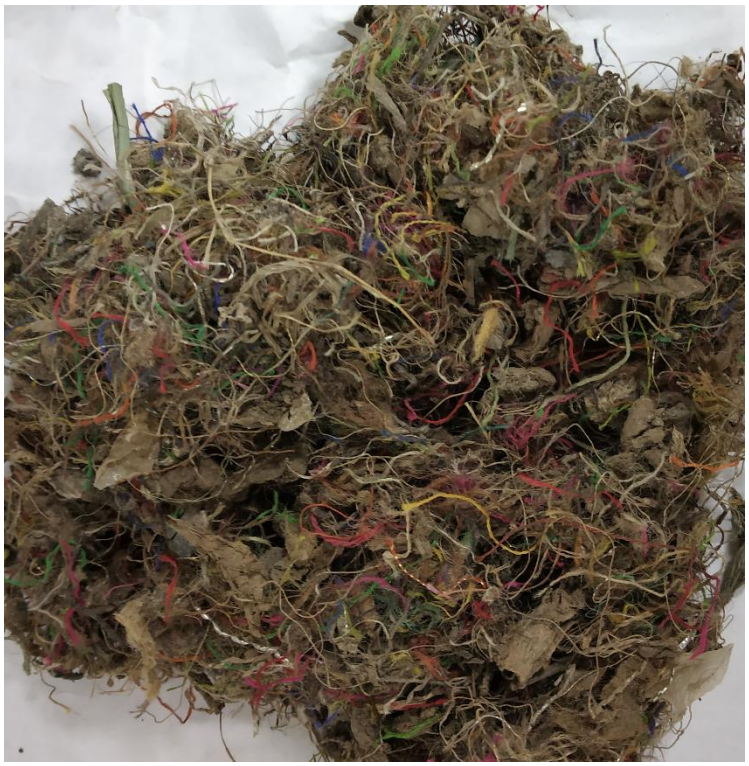
3.3.1.2 Fibers

The sample collected from site-2 Karsada WtE plant was already a 4 mm rejected sample, i.e., it has an average particle size of about 8 to 4 mm (Figure 3.3 (a)). The sample was first dried in an oven at ±60° C for 24 h (to avoid burning) and then the fibers (Figure 3.3 (b)) were separated by an air-blowing method (Figure 3.3(c)), as fibers are the lightest of the other inert matter present in the sample. These fibers were a heterogeneous mixture of different disintegrated materials (e.g., disintegrated parts of clothes, plastic, cardboard, and wood) with an average specific gravity (G_s) and length around 0.82 (from the water displacement method) and 37 mm respectively.

Figure 3.2 Cycle showing collection and segregation of MSW fine fractions

(a)

(b)



(c)

Figure 3.3 (a) 4 mm rejected sample collected from site-2, Karsada waste to energy plant, Varanasi; **(b)** air-blowing method for separating fibers from waste; and **(c)** heterogeneous fiber mix separated from the waste

3.3.2 Laboratory Study

The segregated sample of waste, i.e., MSW fines was tested in a geotechnical engineering laboratory to study their geotechnical, morphological, mineralogical, and chemical characteristics. On reconstituted MSW fines samples, geotechnical characteristics such as specific gravity, grain size analysis, Atterberg limit, standard proctor, consolidation, permeability, California bearing ratio test (CBR), unconfined compression test (UCS), and static triaxial tests were performed. Scanning electron microscope (SEM) analyses were performed on MSW fines to investigate the individual morphology of the MSW fine particles. The atomic structure of crystalline substances present in the considered MSW fine samples was determined using X-ray diffraction (XRD) tests. The major oxides (in weight %) and selected trace elements present in the samples were analyzed using an X-ray fluorescence (XRF) test. Some chemical characteristics of the MSW fines were also determined in the laboratory, i.e., pH, organic content, total dissolved solids, chloride, total dissolved sulphate content, and colour unit. Besides that, the liquefaction and cyclic behaviour of the MSW fines sample were investigated in a series of strain-controlled cyclic triaxial tests (high strain range) and bender element tests (low strain range). The detailed testing programs and methodology for the MSW fines are presented in Table 3.1 to Table 3.3. The testing procedure adopted for each test is discussed in the following sections.

The considered MSW fines are further reinforced with fibers at different percentages for analyzing their strength performance under static and dynamic loading conditions. The fiber-reinforced MSW fines were tested for density variation and consolidation parameters through a series of Proctor tests and consolidation tests, respectively at different fiber content (0, 0.5, 1, 2, 4, and 10%). The optimum percentage of fiber has been considered through static triaxial tests under unconsolidated undrained

(UU) conditions and further strength performance of the optimum composite material is checked under consolidated undrained (CU) and consolidated drained (CD) conditions. The low-strain and high-strain strength behaviour of the fiber-reinforced MSW fines were observed under unconsolidated undrained (UU) and consolidated undrained (CU) conditions through the bender element test and cyclic triaxial test respectively. The detailed testing programs and methodology for reinforced MSW fines are presented in Tables 3.1, 3.2, and 3.4.

Table 3.1 Experimental testing program for physical, chemical, morphological, and geotechnical characteristics.

Material	Experiments	Details of experiments	No. of tests
MSW fines	Physical	Specific gravity tests	1
	Chemical	pH	1
		Organic content	1
		Total dissolved solids	1
		Chloride content	1
		Total dissolved sulphate content	1
		Colour unit test	1
		X-ray diffraction (XRD) test	1
		X-ray Fluorescence (XRF) test	1
	Morphological	Scanning electron microscope (SEM) tests	1
	Geotechnical	Grain size distribution	1
		Atterberg limit tests	1
		Compaction tests	1
		Consolidation tests at R_c=95, 96, 97, 98, 99, and 100 (MDD)%	6
		Permeability tests at R_c=95, 96, 97, 98, 99%	5
		UCS tests at R_c=95, 96, 97, 98, 99%	5
		UU triaxial tests under confining pressures of 50, 100 & 150 kPa and R_c=95, 96, 97, 98, 99, 100 (MDD)%	18
		UU, CU, and CD triaxial tests under confining pressures of 50, 100 & 150 kPa at MDD (sample size 50 mm(D) and 100 mm(H))	9
		CBR tests at R_c=95, 96, 97, 98, 99%	10
	Geotechnical	Compaction tests at FC=0.5, 1, 2, 4, 8, and 10%	6

Fiber-reinforced MSW fines		Consolidation tests at FC=0.5, 1, 2, 4, 8, and 10% at fixed density	6
		UU triaxial tests under confining pressures of 50, 100 & 150 kPa and FC=0.5, 1, 2, 4, 8, and 10% at fixed and varying density	36
		UU, CU, and CD triaxial tests under confining pressures of 50, 100 & 150 kPa at FC=8% and fixed density with sample size 50 mm(D) and 100 mm(H))	9
Total			123
R_c= Relative compaction; UCS= Unconfined compression strength test; UU= Unconsolidated undrained; CU= Consolidated undrained; CD= Consolidated drained; MDD= Maximum dry density; H= Height of the sample; D= Diameter of the sample; CBR=California bearing ratio; FC= Fiber content			

Table 3.2 Standards used for different laboratory tests.

Laboratory tests	Standards
Physical properties	
Specific gravity	IS: 2720 (Part 3/sec1)
Chemical properties	
pH	IS: 2720 (Part 26)
Organic content	IS: 2720 (Part 22)
Total dissolved solids	IS: 2720 (Part 21)
Chloride content	IS: 3025 (Part 32)
Total dissolved sulphate content	IS: 2720 (Part 27)
Colour unit test	IS: 3025 (Part 4)
Geotechnical properties	
Grain size distribution	IS: 2720 (Part 4)
Atterberg limit test	IS: 2720 (part 5)
Compaction test	IS: 2720 (Part 7)
Consolidation test	IS: 2720 (Part 15)
Permeability test	IS: 2720 (part 17)
Unconfined compression test	IS: 2720 (part 10)
Unconsolidated undrained triaxial test	IS: 2720 (Part 11)
Consolidated undrained triaxial test	IS: 2720 (Part 12)
Consolidated drained triaxial test	IS: 2720 (Part 12)
California bearing ratio test	IS: 2720 (Part 16)
Cyclic triaxial test	ASTM D3999 and ASTM D5311
Bender element test	ASTM D2845

3.3.2.1 Morphology, Mineralogy, and Chemical Characteristics Tests

3.3.2.1.1 Scanning Electron Microscope (SEM) Test

The morphological characteristics of the MSW fines sample below 75 microns collected from site-1 (Ramana) were carried out using scanning electron microscope (SEM) techniques available at Central Instrument Facility (CIF), IIT(BHU), Varanasi. The model of the machine used was EVO-Scanning Electron Microscope MA15/18 purchased from the company CARL ZEISS MICROSCOPY LTD with an EHT voltage of 20 kV and 11 mm of working distance for different magnification. Along with the SEM, EDX (Energy Dispersive X-Ray) detector can generate more information about a sample. The 51N1000–EDS System of Oxford Instruments Nanoanalysis company was used along with SEM to detect the elements present in the sample from the SEM images.

EDX works on the principle, that when an electron beam hits the inner shell of an atom it knocks off an electron and leaves a positively charged electron-hole. When an electron is displaced, another electron from the outer shell attracts it to fill the vacancy. This energy difference can be released as an X-ray as the electron moves from the atom's outer higher-energy shell to its inner lower-energy shell. These X-energy rays are unique to the element and transition.

3.3.2.1.2 pH

The pH test was conducted according to IS: 2720 Part 26 (1973). The pH of the sample was directly measured with the help of a pH meter which has been calibrated by the buffer solutions. A solution of 20 gm of MSW fines (< 4.75) mixed with 100 ml of deionized (DI) water was prepared by stirring it for 30 min and letting it stand for an hour.

3.3.2.1.3 Organic Content

The organic content was determined according to IS: 2720 Part 22 (1972). A 5 gm thoroughly mixed sample passing through a 425 μm IS sieve was considered for the test and placed in a conical flask. Using a burette, ten millilitres of N potassium dichromate solution was poured into the conical flask, then carefully 20 millilitres of concentrated sulphuric acid was poured. The mixture was thoroughly swirled for about one minute and allowed to stand for 30 minutes on a heat-insulating surface, such as asbestos or wood for oxidation of organic matter. Then 200 mL of distilled water, 10 ml of orthophosphoric acid, and 1 ml of the indicator were added and vigorously shaken. The ferrous sulphate solution was added in 0.5 ml increments from the second burette, while the contents of the flask are swirled until the colour of the solution changed from blue to green. A further 0.5 ml of potassium dichromate was added to return the solution to its original blue colour. Following the addition of a single drop of ferrous sulphate solution, continue swirling the solution until the colour changes from blue to green. The total volume of ferrous sulphate solution used was recorded for organic content calculations.

3.3.2.1.4 Total Dissolved Solids (TDS)

The TDS calculation and samples were prepared according to IS 2720 Part 21 (1997). About 20g of MSW fines (< 4.75 mm) was mixed with 200 ml water (1:10 dilution) and shaken for 15 hours at 200 rpm. It was then allowed to settle for 24 hours before being decanted through a Whatman filter paper 42. The filtrate was then centrifuged for 15 minutes at 10,000 rpm-1 before being kept at 105°C in a thermostatically controlled oven for gravimetrical analysis of TDS.

3.3.2.1.5 Chloride Content

The chloride was determined on the water aliquot (1:10 dilution) of MSW fines as per IS: 3025 Part 32 (1988). The chloride content was determined through the argentometric method described in the mentioned code.

3.3.2.1.6 Total Dissolved Sulphate

The total dissolved sulphate was determined as per the IS: 2720 Part 27 (1977) on the water aliquot (1:10 dilution) of MSW fines. The standard precipitation method was used for the determination of the total dissolved sulphate content.

3.3.2.1.7 Colour Unit Test

The colour unit of the water extract of the MSW fines (1:10 dilution) was determined through the platinum cobalt (visual comparison) method, as per IS: 3025 Part 4 (1983).

3.3.2.1.8 X-ray Diffraction (XRD) Test

The X-ray diffraction test is based on Bragg's law. This law relates the wavelength of the electromagnetic radiation to the diffraction angle and lattice spacing in a crystalline sample, i.e., $n\lambda = 2d\sin\theta$, where d = inter atomic distance; θ = angle of diffraction of X-ray; λ = wavelength of the incident X-ray and n = an integer equals to one for first order reflections. As the randomly oriented specimen is scanned over an angular range, the diffractometer detects the intensity of the diffracted beam at precise angles. Because each mineral has a unique d-spacing, converting diffraction peaks to d-spacing allows the identification of specific minerals present in the sample. In a glass beaker, 10 gm of MSW fines (passing through a 75 μm IS sieve) was placed, and 5 ml of de-aired water was added. The prepared solution was then randomly mounted on a glass slide and dehydrated for 24

hours. The sample slide was then ready for mineralogy analysis. The X-ray diffraction test was performed using the facility available at Central Instrument Facility (CIF), IIT(BHU), Varanasi. The model of the equipment used was Rigaku Smart Lab 9kW Powder type (without χcradle) purchased from the company RIGAKU Corporation. The compounds present in the MSW fines were detected with a radiation source of Cu-Kα of wavelength (λ) = 1.540 Å at 40 kV and 35 mA. The entire analysis was carried out in 2θ ranging from 20º to 80º with a step size of 0.02º and the scanning speed was set at 1º per min. The interpretation of the obtained XRD pattern was carried out using JCPDS-International Centre for Diffraction Data cards.

3.3.2.1.9 X-ray Fluorescence (XRF) Test

The X-ray Fluorescence (XRF) test was carried out at CSIR - Institute of Minerals and Materials Technology (IMMT), Bhubaneswar. The X-ray fluorescence (XRF) test for oxide content of MSW fines with particle size less than 4.75 mm was performed with a Zetium XRF spectrometer (Malvern Panalytical, The Netherlands) with a maximum capacity of 4 kW.

3.3.2.2 Geotechnical Characterization Tests

The detailed procedure adopted for conducting various geotechnical tests (specific gravity, grain size analysis, Atterberg limit, standard proctor, consolidation, permeability, CBR, UCS, and static triaxial tests) are presented in the following sections for unreinforced and reinforced MSW fines.

3.3.2.2.1 MSW Fines

3.3.2.2.1.1 Grain size distribution

To determine the particle size of the MSW fines samples, grain size distribution analysis was performed according to IS 2720 Part 4 1(985). The MSW samples from the field were first sieved, and the mass of the sample passing through 75 sieves was taken for hydrometer analysis. The gradation curve of the considered material was created by combining the results of the sieve and hydrometer analysis.

3.3.2.2.1.2 Atterberg limit test

The Atterberg limit test (liquid limit and plastic limit) of the MSW fines was carried out as per the IS 2720 Part 5 (1985). The liquid limit was determined through the Fall cone penetrometer test.

3.3.2.2.1.3 Compaction test

A standard Proctor test (light compaction test) was performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the MSW fines sample as per IS 2720 Part 7 (1980). The sample was thoroughly mixed with enough water after it had been oven dried (at 105 °C). The mixture was then placed in the Proctor mould and compacted in three layers, receiving 25 blows per layer from a height of 30 cm with a 2.5 kg rammer. The procedure was repeated by increasing the amount of water until the wet unit weight of the compacted MSW fines sample decreased or remained unchanged.

3.3.2.2.1.4 Compressibility characteristics

The one-dimensional consolidation tests were used to investigate the compressibility characteristics of the MSW fines sample (according to IS 2720 Part 15 (1986). The samples were considered at 6 different relative compactions (R_c), i.e., 95 to

100% (MDD). The prepared samples were soaked for 24 hours in a consolidation ring with a seating load of 5 kPa. Following that, loading and unloading were performed as per IS 2720 Part 15 (1986).

3.3.2.2.1.5 Permeability test

The falling head permeameter was used to calculate the coefficient of permeability (k) of the MSW fines sample at different R_c (95 to 99%). The tests were performed using a rigid wall compaction mould permeameter as per IS 2720 Part 17 (1986). The samples were prepared and placed in the permeameter using standard compaction techniques. The sample was then saturated with de-aired water. The inlet nozzle of the mould was connected to the standpipe, and water flow was allowed until a steady flow was achieved. The time interval for a head fall in the standpipe was then recorded and repeated five times to determine the time interval for the same head.

3.3.2.2.1.6 Unconfined compression strength test (UCS)

The unconfined compressive strength of the MSW fines at different R_c (95 to 99%) was determined as per IS: 2720 Part 10 (1991). The considered sample size was 38 mm (diameter) and 76 mm (height), compacted in 3 layers by the moist tamping method (Degregorio, 1990).

3.3.2.2.1.7 Triaxial tests

To determine the shear strength parameters of the considered MSW fines the static triaxial tests were conducted under three conditions, i.e., Unconsolidated Undrained (UU), Consolidated Undrained (CU), Consolidated drained (CD).

Unconsolidated undrained (UU) triaxial test

The static UU triaxial tests were conducted according to the IS: 2720 Part 11 (1993). About 18 samples of sizes 38 mm (diameter) and 76 mm (height) prepared through the moist tamping technique were tested under three confining pressures (50, 100, and 150 kPa) and five different R_c (95 to 99%) and MDD (R_c =100%). The strain rate was maintained at 1.2 mm/min. The samples were unconsolidated and drainage was not allowed during the whole test. Another set of three tests at maximum dry density (MDD) was conducted under three confining pressures (50, 100, and 150 kPa) with a sample size of 50 mm (diameter) and 100 mm (height). The sample preparation technique was the same for every triaxial test condition and is discussed in the following section in detail.

Consolidated undrained (CU) triaxial test

The static CU triaxial tests were conducted according to the IS 2720 Part 12 (1981). The moist tamping technique (Degregorio, 1990) was used for the preparation of 50 mm diameter and 100 mm height MSW fines samples at MDD of the considered material. A total of three samples were tested under the confining pressures of 50, 100, and 150 kPa. Each sample was prepared in four layers by compacting with a tamping rod (nearly 48 mm in diameter) and giving each layer a fixed number of blows. The sample was then covered with filter paper and porous stone on top and bottom. After pulling the rubber membrane over the sample and sealing the assembly with the o-rings. After mounting the sample saturation process was continued until the Skempton's Pore Pressure Parameter B ($B = \Delta u/\Delta\sigma_c$, Δu = change in pore pressure, and $\Delta\sigma_c$ = change in confining pressure) reaches almost 0.99. Once the sample was completely saturated, it was consolidated to a desired effective confining pressure, and the volume change was recorded. Then the shearing was

carried out under the confining pressure of 50, 100, and 150 kPa without allowing drainage during shearing.

Consolidated drained (CD) triaxial test

The static CU triaxial tests were conducted according to the IS 2720 Part 12 (1981). The three standard samples of MSW fines of size 50 mm in diameter and 100 mm in height were tested under the confining pressures of 50, 100, and 150 kPa. The sample preparation, saturation, and consolidation steps were similar to the CU triaxial test. The only difference was in the shearing phase as drainage was allowed during this test.

3.3.2.2.1.8 California bearing ratio (CBR) test

The CBR tests were carried out according to the IS 2720 Part 16 (1987). The CBR tests were conducted for 5 different R_c (95 to 99%) under unsoaked and soaked conditions. The soaking period of 96 hours was maintained before going for soaked CBR tests.

3.3.2.2.2 Fiber-Reinforced MSW Fines

3.3.2.2.2.1 Compaction test

A standard Proctor test (light compaction test) was performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the MSW fines reinforced with fibers samples at different fiber content (0.5, 1, 2, 4, 8, and 10%) as per IS 2720 Part 7 (1980). The fibers were mixed in desired quantity by replacing them in percentage by weight of the considered MSW fines.

3.3.2.2.2.2 Compressibility characteristics

The compressibility characteristics of MSW fines reinforced with fibers were investigated by one-dimensional consolidation tests (according to IS 2720 Part 15 (1986).

The samples were prepared at six different fiber content (FC) of 0.5, 1, 2, 4, 8, and 10%. The mixed samples were compacted in the consolidation ring keeping a fixed density of 1.51 g/cc (MDD of MSW fines). The loading and unloading of the samples were done according to the IS standard.

3.3.2.2.2.3 Triaxial tests

To determine the shear strength parameters of the fiber-reinforced MSW fines, the static triaxial tests were conducted under three conditions, i.e., Unconsolidated Undrained (UU), Consolidated Undrained (CU), Consolidated drained (CD).

Unconsolidated undrained triaxial test

The static UU triaxial tests on fiber-reinforced MSW fines were conducted according to the IS: 2720 Part 11 (1993). The tests were conducted by mixing fibers in six different percentages, i.e., 0.5, 1, 2, 4, 8, and 10%. A set of two MSW fines reinforced with fibers (sample size of 38 mm (diameter) and 76 mm (height)) for static UU triaxial tests were conducted each having a set of six tests at confining pressure of 50, 100, and 150 kPa. The first set consists of the samples made at densities obtained through the fiber-mixed MSW fines at a particular percentage of finer content and the second set consists of tests at a fixed density (1.51 gm/cc, i.e., the MDD of MSW fines). The MSW fines were mixed with fibers by replacing the fines at the required percentage by weight and thoroughly mixing with the required water content. The samples prepared were moist tamped in layers like the samples of MSW fines as discussed in the above section (**3.3.2.2.1.7.1)**. In addition, a set of three tests at the optimum fiber content of 8% (fixed density) was conducted under three confining pressures (50, 100, and 150 kPa) with a sample size of 50 mm (diameter) and 100 mm (height).

Consolidated undrained triaxial test

The static CU triaxial tests on fiber-reinforced MSW fines were conducted according to the IS 2720 Part 12 (1981). A set of three tests at the optimum fiber content of 8% (fixed density) was conducted under three confining pressures (50, 100, and 150 kPa) with a sample size of 50 mm (diameter) and 100 mm (height). The sample preparation was discussed in the above section.

Consolidated drained triaxial test

The static CD triaxial tests on fiber-reinforced MSW fines were conducted according to the IS 2720 Part 12 (1981). A set of three tests at the optimum fiber content of 8% (fixed density) was conducted under three confining pressures (50, 100, and 150 kPa) with a sample size of 50 mm (diameter) and 100 mm (height). The sample preparation was discussed in the above section.

3.3.2.3 Strain-Controlled Cyclic Triaxial Tests

A series of 104 stain-controlled triaxial tests (CU and UU) were performed on the reconstituted samples of MSW fines (Table 3.3). To investigate the liquefaction and cyclic behaviour of the compacted MSW fines, consolidated undrained (CU) tests were performed on MSW fines samples. The parametric study was done by considering the four different parameters, i.e., relative compaction (90, 92, 94, 96, and 98 %), confining pressure (50, 70, and 100 kPa), frequency (0.3, 0.5, and 1), and axial strain (0.4, 0.6, 0.8, and 1) to check the effect of these parameters on dynamic properties. All the samples were prepared and maintained at 50 mm (diameter) and 100 mm (height). The sample preparation techniques were the same as described for the static triaxial test for unreinforced and reinforced MSW fines.

In addition, the CU and UU tests were conducted on fiber-reinforced MSW fines to check the cyclic behaviour of the inclusion of fibers at different FC (fiber content). The testing program is provided in Table 3.4 where samples were prepared and tested at a fixed density (MDD of MSW fines, i.e., R_c =100%), confining pressure (σ_c =100 kPa), and frequency (f =1Hz).

Table. 3.3 Testing program for MSW fines under cyclic loading condition (Cyclic triaxial test).

Test type	R_c (%)	σ_c or σ'_c (kPa)	f (Hz)	ε (%)	No. of test
UU	100 (MDD)	100	1	1	1
CU	90	100	1	0.4	1
	90	100	1	0.6	1
	90	100	1	0.8	1
	90	100	1	1	1
	92	100	1	0.4	1
	92	100	1	0.6	1
	92	100	1	0.8	1
	92	100	1	1	1
	94	100	1	0.4	1
	94	100	1	0.6	1
	94	100	1	0.8	1
	94	100	1	1	1
	96	100	1	0.4	1
	96	100	1	0.6	1
	96	100	1	0.8	1
	96	100	1	1	1
	98	100	1	0.4	1
	98	100	1	0.6	1
	98	100	1	0.8	1
	98	100	1	1	1
	90	70	1	0.4	1
	90	70	1	0.6	1
	90	70	1	0.8	1
	90	70	1	1	1
	92	70	1	0.4	1
	92	70	1	0.6	1
	92	70	1	0.8	1
	92	70	1	1	1
	94	70	1	0.4	1
	94	70	1	0.6	1
	94	70	1	0.8	1
	94	70	1	1	1

	96	70	1	0.4	1
	96	70	1	0.6	1
	96	70	1	0.8	1
	96	70	1	1	1
	98	70	1	0.4	1
	98	70	1	0.6	1
	98	70	1	0.8	1
	98	70	1	1	1
	90	50	1	0.4	1
	90	50	1	0.6	1
	90	50	1	0.8	1
	90	50	1	1	1
	92	50	1	0.4	1
	92	50	1	0.6	1
	92	50	1	0.8	1
	92	50	1	1	1
	94	50	1	0.4	1
	94	50	1	0.6	1
	94	50	1	0.8	1
	94	50	1	1	1
	96	50	1	0.4	1
	96	50	1	0.6	1
	96	50	1	0.8	1
	96	50	1	1	1
	98	50	1	0.4	1
	98	50	1	0.6	1
	98	50	1	0.8	1
	98	50	1	1	1
	90	100	0.5	0.4	1
	90	100	0.5	0.6	1
	90	100	0.5	0.8	1
	90	100	0.5	1	1
	92	100	0.5	0.4	1
	92	100	0.5	0.6	1
	92	100	0.5	0.8	1
	92	100	0.5	1	1
	94	100	0.5	0.4	1
	94	100	0.5	0.6	1
	94	100	0.5	0.8	1
	94	100	0.5	1	1
	96	100	0.5	0.4	1
	96	100	0.5	0.6	1
	96	100	0.5	0.8	1
	96	100	0.5	1	1
	98	100	0.5	0.4	1
	98	100	0.5	0.6	1
	98	100	0.5	0.8	1
	98	100	0.5	1	1

	90	100	0.3	0.4	1
	90	100	0.3	0.6	1
	90	100	0.3	0.8	1
	90	100	0.3	1	1
	92	100	0.3	0.4	1
	92	100	0.3	0.6	1
	92	100	0.3	0.8	1
	92	100	0.3	1	1
	94	100	0.3	0.4	1
	94	100	0.3	0.6	1
	94	100	0.3	0.8	1
	94	100	0.3	1	1
	96	100	0.3	0.4	1
	96	100	0.3	0.6	1
	96	100	0.3	0.8	1
	96	100	0.3	1	1
	98	100	0.3	0.4	1
	98	100	0.3	0.6	1
	98	100	0.3	0.8	1
	98	100	0.3	1	1
	100 (MDD)	100	1	0.4	1
	100 (MDD)	100	1	0.6	1
	100 (MDD)	100	1	0.8	1
Total No. of tests					104
R_c= Relative compaction; σ_c= Confining pressure; σ'_c= effective confining pressure; f= Frequency; ε= Axial strain; MDD= Maximum dry density					

Table 3.4 Testing program for fiber-reinforced MSW fines under cyclic loading condition (Cyclic triaxial test).

Test type	Fiber content (%)	Axial strain (%)	No. of tests
UU			
	0.5	1	1
	1	1	1
	2	1	1
	4	1	1
	8	1	1
	10	1	1
CU			
	0.5	0.4,0.6.0.8	3
	1	0.4,0.6.0.8	3
	2	0.4,0.6.0.8	3
	4	0.4,0.6.0.8	3
	8	0.4,0.6.0.8	3
	10	0.4,0.6.0.8	3
Total number of tests			24
All tests were conducted at constant density=1.51g/cc, frequency=1 Hz, and confining or effective confining pressure =100 kPa			

3.3.2.3.1 Testing Equipment

A computerized semi-automated triaxial testing equipment with the facility of both static and dynamic testing, supplied by M/s. HEICO, New Delhi, India, was used for this study. The equipment consists of a submersible load cell of capacity ±5 kN with an accuracy of 0.001 kN and a displacement transducer of ±50 mm (with 0.01 mm accuracy) and ±10 mm (with 0.01 mm accuracy). The pore pressure transducers have a range of 0–2,000 kPa and an accuracy of 1.0 kPa fitted at the back side of the base of the triaxial cell. The load frame can accommodate triaxial cells with sample sizes ranging from 38 mm to 100 mm in diameter with a length-to-diameter ratio of 2:1. Both stress-controlled and strain-controlled tests can be performed using a hydraulic-controlled loading system. A hydraulic power supply (power pack) is provided to provide the required flow and pressure for hydraulic actuator actuation. The pneumatic control panel is a component of the cyclic

triaxial system that ensures accurate confining and back pressure using the compressed air produced by the air compressor. The cell pressure and back pressure are controlled manually through precise regulators. By using an external input, the equipment can vary the frequency range from 0.01 Hz to 10 Hz with various waveforms such as sine, triangular, rectangular, square, or any other. The specification of the cyclic triaxial test equipment is presented in Table 3.5. The photographic view of the equipment and accessories used is shown in Figure 3.4.

The signal conditioning unit provides excitation to all transducers and receives the output from all transducers, amplifies and processes the signals as per the requirement, and transfers it to the data accumulation card in the computer attached. To analyze the test results, separate software is provided as per ASTM 3999 and ASTM 531.

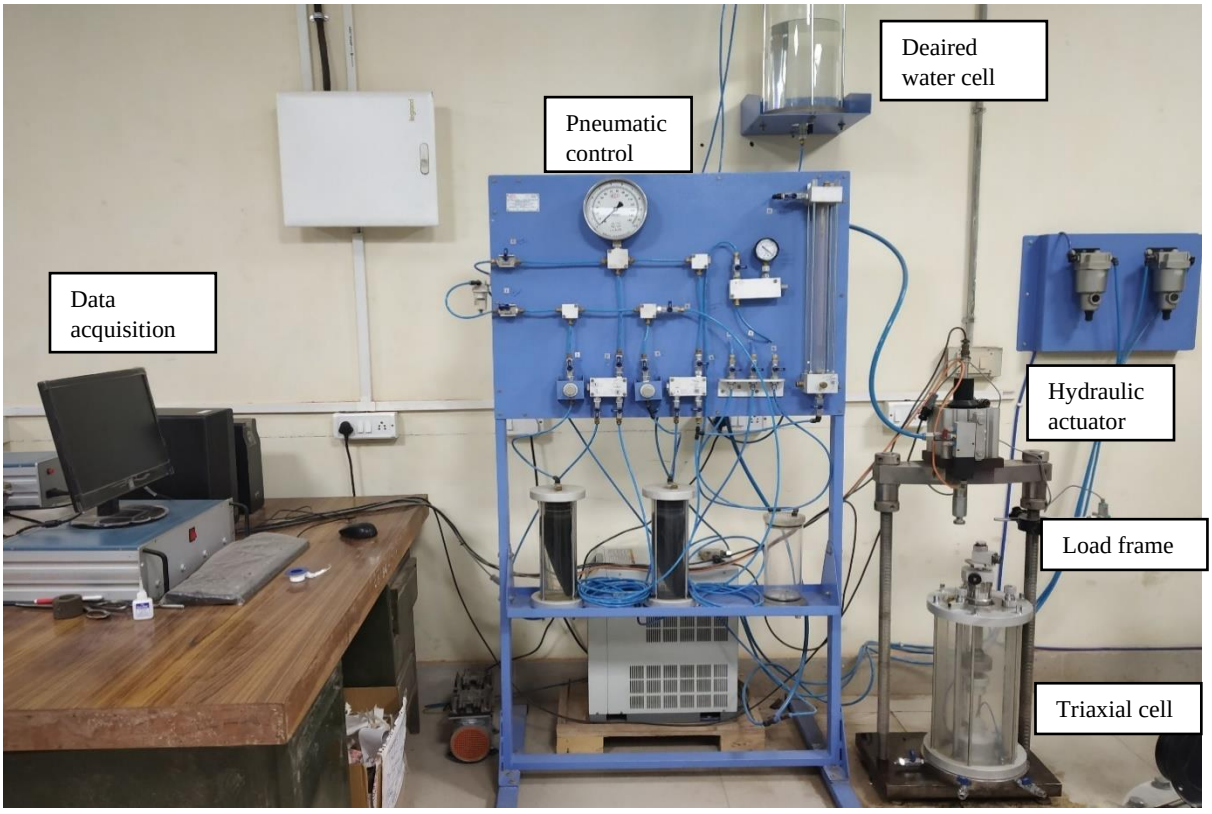


Figure 3.4 Photographic view of the strain-controlled cyclic triaxial testing equipment

Table 3.5 Specification of cyclic triaxial test equipment.

Pneumatic pressure control panel accessories	Specifications
Confining pressure	Up to 10 kg/cm^2
Back pressure	Up to 10 kg/cm^2
Volume change	80 cc
De-aired chamber	10 litres
Compressor	10 Bar pressure with 200 litres tank
Vacuum pump	Creates a vacuum of 70 cm of mercury
Triaxial cell accessories	
Test possible	Static and dynamic (compression/ extension or both
Specimen size	Up to 100 mm diameter and 200 mm height
Transducers	
Submersible load cell	±5 kN (0.001 kN)
Displacement transducer	±50 mm (0.01 mm) and ±10 mm (0.001 mm)
Pore pressure transducer	20 kg/cm^2 (0.01 kg/cm^2)

3.3.2.3.2 Test Procedure

The samples of 50 mm in diameter and 100 mm in height were prepared by moist tamping technique (Degregorio, 1990). For the MSW fines samples, the dry MSW fines were mixed with the required water content from the compaction curve to maintain the desired *Rc* (90, 92, 94, 96, 98, and 100% (MDD)). The sample was compacted in four layers and each layer was compacted with a tamping rod (nearly 48 mm in diameter) using a predetermined number of blows to achieve the desired uniform density. Then the filter paper and porous stones were placed on top and bottom of the sample. After this rubber membrane was pulled over the sample and the assembly was sealed with an O-ring. Similarly, the samples of reinforced MSW fines were prepared in layers, also discussed in section **3.3.2.2.2.1.3.** The fiber-reinforced MSW fines samples were prepared by mixing

the MSW fines with desired fiber content (FC), i.e., 0.5, 1, 2, 4, 8, and 10%. The stages of sample preparation and mounting are shown in Figure 3.5.

There are generally three steps in the triaxial test after preparation and mounting of the sample, i.e., saturation, consolidation, and shearing. The shearing can be done at desirable loading conditions (static/dynamic). In the unconsolidated undrained (UU) triaxial test, the first two steps were not considered and the prepared samples were directly sheared under the desired dynamic loading conditions and the number of cycles. The CU tests follow all three steps.

Once the sample was mounted in the triaxial cell, the saturation process was continued by increasing the back pressure at regular intervals while keeping the effective confining pressure at 20 kPa and the Skempton's pore water parameter (B) ($B = \Delta u/\Delta\sigma_c$, Δu = change in pore pressure, and $\Delta\sigma_c$ = change in confining pressure) was periodically monitored until a value of 0.99 was achieved indicating that the specimen was essentially saturated.

Once the saturation was achieved up to 99%, it was isotopically consolidated to a desired effective confining pressure. If there is no variation in the volume change readings and the pore pressure remains stable during that period, the consolidation process is assumed to be completed.

After the consolidation process, the sample was subjected to strain-controlled cyclic loading in the vertical direction using a hydraulic actuator. The cyclic shearing of the MSW fines and reinforced MSW fines were carried out in the laboratory under different relative compactions, confining pressures, frequencies, and cyclic shear strain amplitudes as per the ASTM D5311 (1992) and ASTM D3999 (1996). All samples were cyclically loaded until they failed, i.e., the excess pore pressure ratio attained one for CU cyclic triaxial tests. The

data acquisition system was used to record the axial deformation, confining pressure, pore water pressure, cyclic load, and the number of cycles.

The two fundamental dynamic parameters computed from the cyclic triaxial tests were dynamic shear modulus (G) and damping ratio (D). Both the parameters were computed through the hysteresis loop as shown in Figure 3.6, where G is obtained from the slope of the line connecting the maximum and minimum stress-strain curve, and D represents the energy dissipation in each cycle (i.e., the ratio of dissipated energy to the total energy applied). The dynamic shear modulus and damping ratio were computed according to ASTM D3999 (1996).

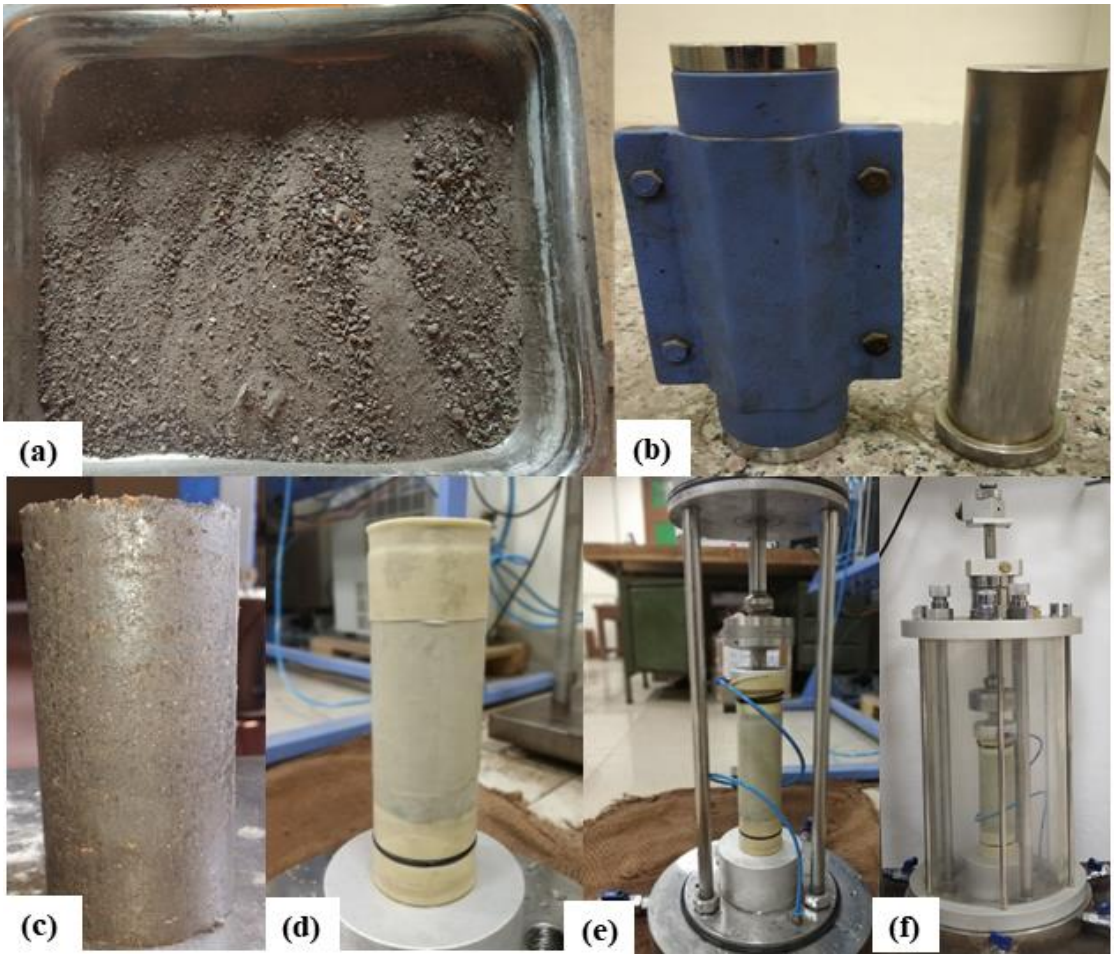


Figure 3.5 Stages of sample preparation and mounting for cyclic triaxial test

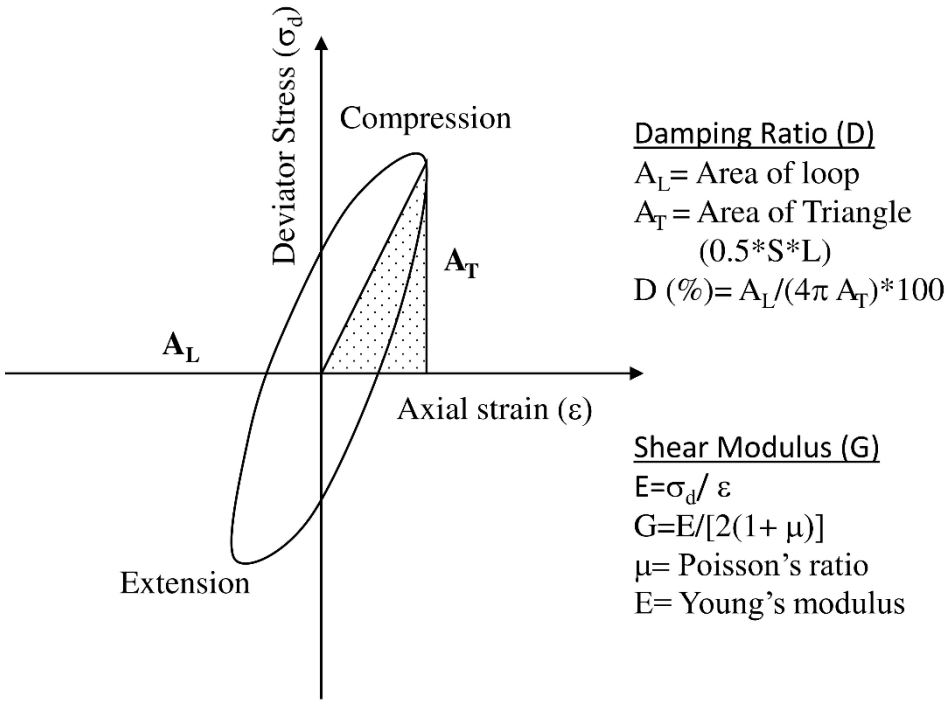


Figure 3.6 Schematic of typical hysteresis loop

3.3.2.4 Bender Element Test

Piezoelectricity is the basic principle of the bender element test, which was first invented by Jacques and Pierre Curie in 1880. The bender element test consists of a triaxial cell attached to the piezoelectric element on both ends. These piezoelectric elements have the property to convert electrical energy to mechanical energy when get excited with an electric voltage. The generated mechanical waves get received by another piezoelectric element on the other end which converts that mechanical energy to the electric signal. The equipment records the time lag between the generated input signal and the received output signal. As the distance traveled is fixed which gives the velocity of the wave generated.

3.3.2.4.1 Testing Equipment

The equipment, supplied by M/s. HEICO, New Delhi, India consists of main four units (shown in Figure 3.7).

1. Triaxial Cell with bender element for a sample size of 50 mm diameter.
2. Dual Channel high-performance digital oscilloscope.

3. Dual Channel Function Generator (waveform generator): adopts advanced DDS technology, dual channel output, 100 MSa/s sampling rate, 14-bit vertical resolution (or better).
4. Amplifier (convertor unit) for a better representation of the waveform on the oscilloscope screen.

The two channels were attached from the convertor unit to the triaxial cell for transmitting and receiving the signals. The bender elements were attached to the triaxial cell as shown in Figure 3.8. The upper end is the transmitter from where the waves get entered into the sample and the lower one is the receiver end. The convertor unit of the amplifier was attached to the waveform generator. The waveform generator was used to give input data, i.e., type of input signal (Sine, Triangular, Square, Random waveforms, and Ramp signal); frequency of wave; amplitude, etc. The generated input wave as per the given specification was received by the transmitter end of the triaxial cell and waves travel through the sample and are received by the receiver end and send back to the convertor unit. The convertor unit and waveform generator were connected to the digital oscilloscope which displays the input and output signals. A typical display of input (yellow) and output (blue) waves on an oscilloscope screen are shown in Figure 3.9.

Figure 3.7 Bender element apparatus setup

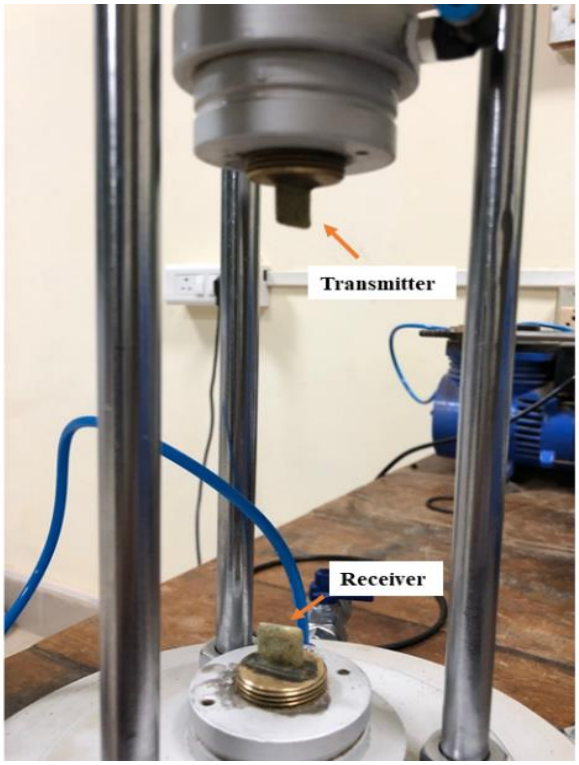


Figure 3.8 Bender element attached to the triaxial cell

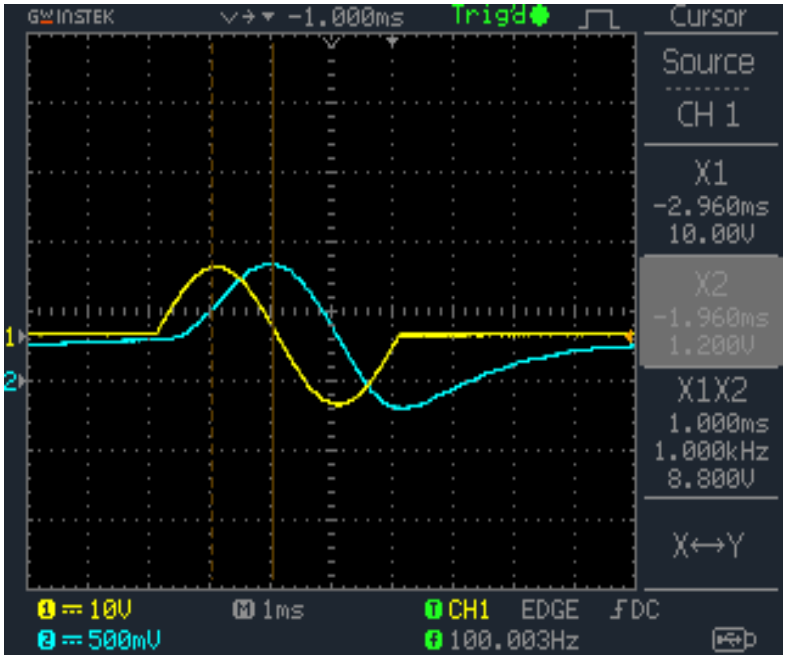


Figure 3.9 A typical input and output wave presented on an oscilloscope display

3.3.2.4.2 Test Procedure

The samples for the bender element test were prepared as they were prepared in the case of the cyclic triaxial test. The sample size was fixed, i.e., 50 mm (diameter) and 100 mm (height). Once the sample was prepared the groves of the size of bender elements (almost 1.3 cm each) were made on both ends and then it was mounted on the triaxial cell (Figure 3.10). The test was conducted on MSW fines and fiber-reinforced MSW fines in saturated and unsaturated conditions. The samples of MSW fines were tested under five different relative densities (90, 92, 94, 96, and 98%), confining pressure of 0 to 200 kPa (unsaturated samples) and 100 kPa (saturated sample), and frequency (0.25 to 1.5 kHz). The fiber-reinforced MSW fines were tested for the fixed density of 1.51 g/cc (MDD of the MSW fines), confining pressure of 0 to 200 kPa (unsaturated samples) and 100 kPa (saturated sample), and frequency (0.25 to 2 kHz). The testing program of the bender

element test is shown in the flowchart (Figure 3.11). The bender element test was performed as per the ASTM D2845 (2000).

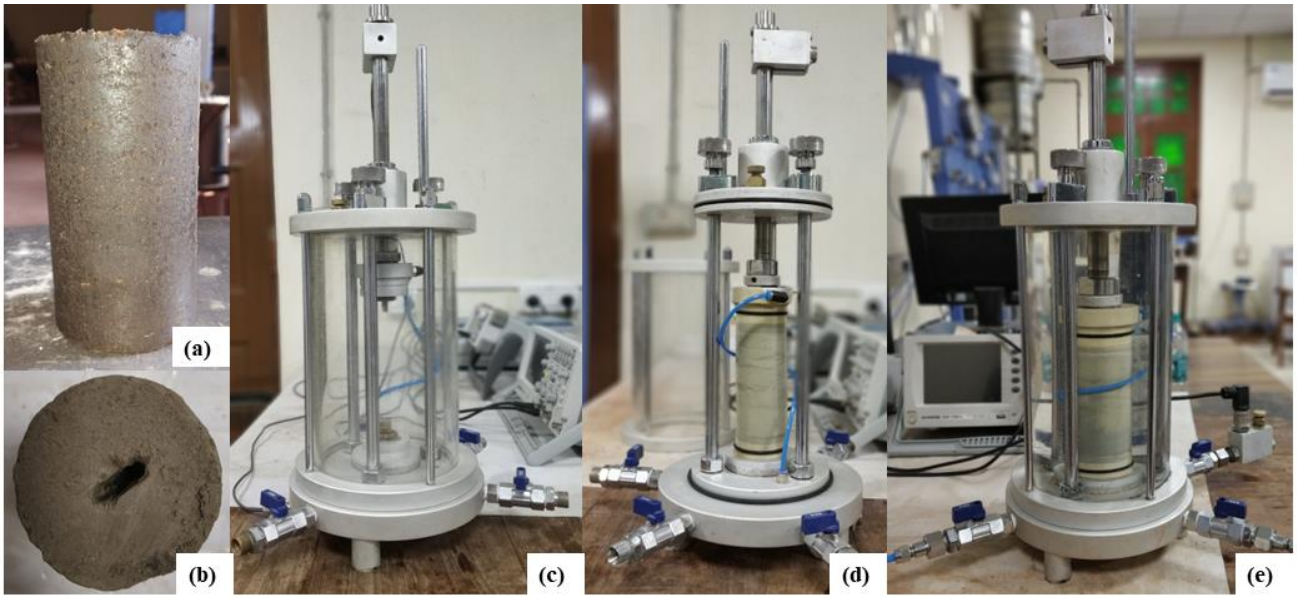


Figure 3.10 Stages of sample preparation and mounting for bender element test

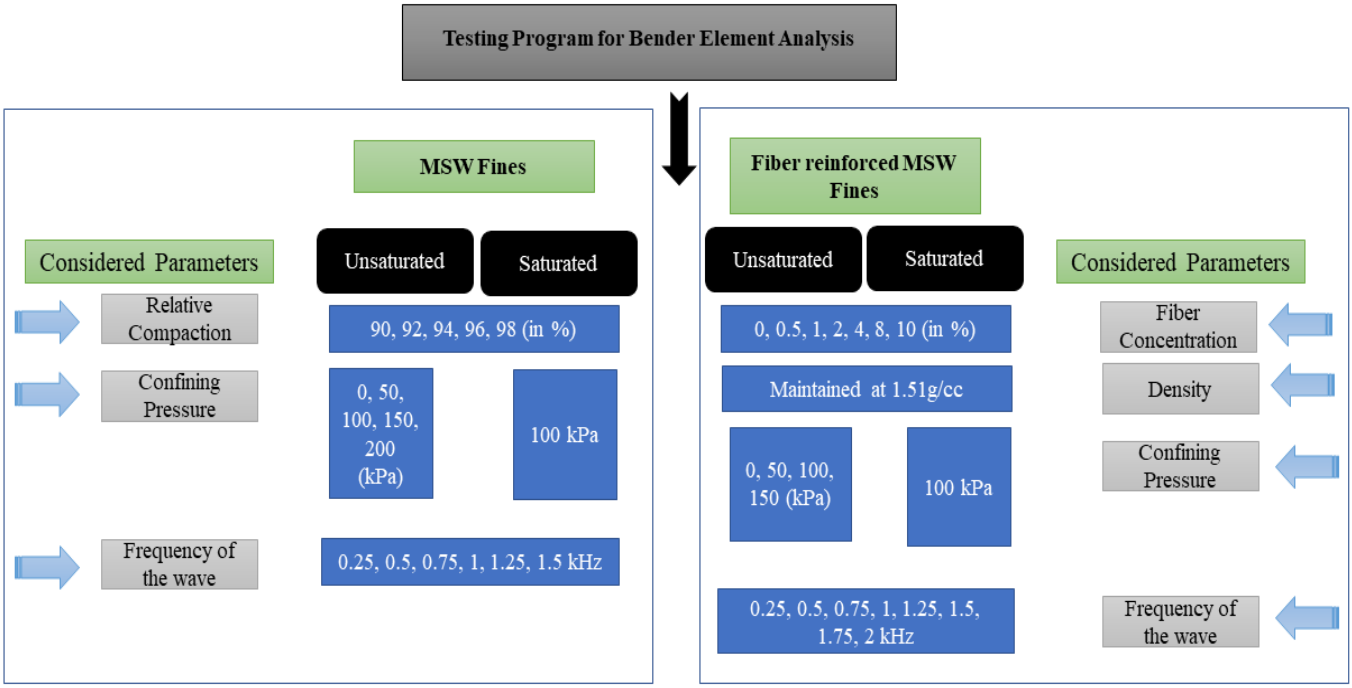


Figure 3.11 Testing program flow chart for the bender element test

The equipment is commonly used to find the small-strain shear modulus by applying the following expression (Equation 3.1):

$$G_{max} = \rho {V_s}^2 = \rho \left(\frac{L}{\Delta t}\right)^2 \quad (3.1)$$

where ρ = bulk mass density of the material (kg/m^3); *Vs*=velocity of the shear wave (m/sec), L= travel length of the wave, and Δt is the travel time taken by the waves. The travel length of the wave is the effective length of the sample, i.e., the height of the sample (100 mm) subtracting the length of the bender elements from both sides.

The measured travel time of the wave is an important factor in the bender element test, which can be determined using an oscilloscope. To estimate the travel time of the waves, either time domain or frequency domain methods can be used. There are various approaches available for measuring the travel time in a time domain analysis, such as start-to-start (S.S.), peak-to-peak (P.P.), and cross-correlation (C.C.) (Viggiani and Atkinson, 1995; Yamashita et al., 2009; Kawaguchi et al., 2016). Travel time is defined in the start-to-start (S.S.) approach as the time taken by the wave to travel from the starting position of the transmitting wave to the starting position of the receiving wave (Δts). In the peak-to-peak (P.P.) approach, the travel time is the time taken by the wave to travel from the peak of the transmitting wave to the peak of the receiving wave (Δtp). In the cross-correlation method, it is a time difference function that measures the similarity of the transmitted and received waves. It can be calculated using Equation 3.2 below.

$$\mathrm{CCxy}(\tau) = \lim_{T=\infty} \frac{1}{T} \int_0^T X(t) Y(t+\tau) dt \quad (3.2)$$

where X(t)=input signal, Y(t)=output signal, T=total time travel, and τ=time shift between input and output signal.

The travel time in the frequency domain method is determined using phase velocity and assumes that the input wave frequency is equal to the output wave frequency. The cross-phase spectrum of the generated and received waves can be used to calculate the phase velocity. The travel time difference estimated by the frequency domain method differs significantly from that estimated by the time domain method. As a result, time domain analysis is preferred for determining the time delay.