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NON DESTRUCTIVE TESTING FOR EPS GEOFOAM QUALITY ASSURANCE

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Abstract

Expanded Polystyrene (EPS) geofoam is a compressible lightweight fill material. The quality of the EPS geofoam supplied must be inspected thoroughly before its placement in a project site. A review of the quality assurance measures put forward by different construction authorities around the globe was performed. It was found that the quality measures cited by these authorities are not representative of actual full sized EPS geofoam block properties. Hence, these measures have room for more revision and improvement for an effective and efficient quality assurance measure both at the EPS geofoam production plant and on the project site. Moreover, a comparison of case studies showed that in the absence of a strict quality assurance measure, uneven settlements had occurred in road way constructed over EPS geofoam which eventually led to the removal and replacement of the entire EPS geofoam fill. Non Destructive Testing, specifically P waves, were used to check the mechanical properties of EPS geofoam blocks of different densities which were produced at four different EPS production plants. The relationship between P wave velocities were checked against the different EPS densities tested. Additional relationships were examined between P wave velocities through a virgin EPS geofoam block (without any regrind/recycled content) and another EPS block of the same density which had a specific percentage of regrind/recycled content. The effect of using a signal amplifier on EPS virgin blocks and blocks containing regrind was studied. Excessively high P wave velocity variations within an EPS geofoam block was tied to the use of EPS resin beads that were not recommended for that density of geofoam. Pentane loss and the use of a resin bead type with non-uniform sizes are also believed to have caused

additional variations in the P wave velocity of the blocks. EPS geofoam blocks with regrind content transmitted slower velocity and lower amplitude P waves than their virgin counterparts for the same density. Furthermore, information provided from prior large scale tests performed on EPS geofoam were found to agree with the Young's modulus values obtained by using the P wave velocities. Finally, the use of P wave velocity as a quality assurance measure on an EPS geofoam block is found to be effective and practical and is recommended to be incorporated in the various construction quality standards that pertain to EPS geofoam blocks.

NON DESTRUCTIVE TESTING FOR EPS GEOFOAM QUALITY ASSURANCE

By

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Thesis

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1 Introduction

1.1 EPS production and types

Expanded polystyrene (EPS) geofoam is a lightweight material that is used in a number of applications that range from construction projects to packaging of goods. Production of EPS geofoam blocks start with the usage of a polystyrene polymer as a raw material (Geofoam Resarch Center, 2000). Expandable polystyrene beads are produced from the styrene monomer; by a process known as polymerization (Gibson & Ashby, 1988). The number and length of the polystyrene beads produced depend on the amount of catalyst used in the polymerization process (Geofoam Resarch Center, 2000).

Figure 1.1 Shipment containers of polystyrene resin beads (image from field testing)

The Expandable polystyrene beads are shipped to EPS geofoam production companies in large sealed bags or boxes of 1 ton weight as the ones shown in Figure 1.1. At the production companies, as the first step in EPS geofoam production, the expandable polystyrene beads go through a pre-expansion process in either a continuous or batch expander vessel to produce pre puffs. The pre-expansion process involves the enlargement of the resin. These expanded pre puffs have an increased volume which is around fifty times larger than the volume of the raw polystyrene beads (BASF, 1996). The density of the pre puffs are determined by controlling the heat and the duration the beads stay in the expander.

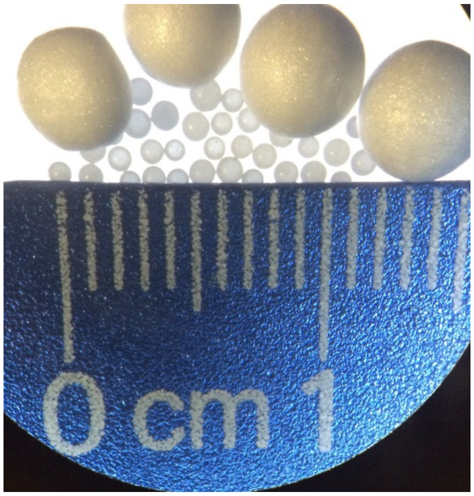


Figure 1.2 Resin beads and pre puffs

The pre puffs are then dried in either open air or a bed drier (Geofoam Resarch Center, 2000) before they are moved to large storage silos (shown in Figure 1.3) where they are aged. In the aging step, the pre puffs are allowed to normalize with the atmospheric pressure and room temperature.

The next phase in EPS geofoam production is the molding stage. In this stage, the pre puffs are transferred to either a shape or a block molder, where, under a high temperature and pressure, the pre puffs are allowed to expand and fuse to one another to create a desired shape or a solid rectangular prism, respectively. The dimensions of the block molds vary from manufacturer to manufacturer and is discussed later in this thesis. The newly produced blocks are then allowed to cure for a minimum of 24 hours before shipment to application sites. Finished blocks are also cut into required shapes and sizes by using a hot wire cutter (Figure 1.4 shows half sized block cut using the hot wire cutter). Depending on the application for the EPS geofoam block, regrind or recycled portion is added in the expansion phase in the block mold. Regrind material in most cases is material that is left over from the cutting of the blocks to different shapes. Lower density geofoam blocks with regrind percentages that vary from 10% - 35% are mostly used for packaging purposes.

Figure 1.3 Aging silos approximately 2 X 6 X 6 m (image from field testing)

Figure 1.4 Half sized block

EPS geofoam blocks vary in density. Table 1-1 summarizes the types of EPS blocks and their respective densities.

1.2 Specification and acquisition of EPS geofoam

Common design considerations as per ASTM D7180/D7180M – 05 (reapproved 2013) for specifying the use of EPS geofoam are listed as follows:

- Compressive strength properties

- Load distribution requirements
- Subgrade requirements
- Layout of blocks
- Dimensional tolerances
- Buoyancy
- Thermal insulation properties (R Value)
- Exposure to UV light
- Flammability and exposure to hydrocarbons

Out of these considerations, the compressive strength and thermal insulation properties are physical properties of EPS geofoam that are determined by performing tests on specimens cut from a full block.

Table 1-1 EPS geofoam types from ASTM D6817/D6817M – 15

Types	**Density, kg/m^3 (lb/ft^3)**
EPS 12	11.2 (0.70)
EPS 15	14.4 (0.90)
EPS 19	18.4 (1.15)
EPS 22	21.6 (1.35)
EPS 29	28.8 (1.80)
EPS 39	38.4 (2.40)
EPS 46	45.7 (2.85)

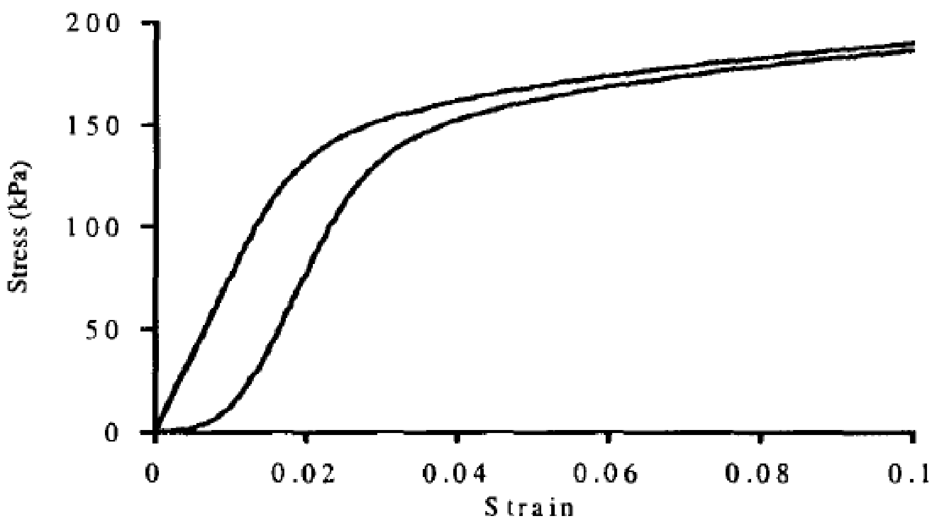


Figure 1.5 Corrected and uncorrected stress - strain plot for a 50 mm cube EPS 29 sample tested in compression *(Elragi, Negussey, & Kyanka, 2000)*

Figure 1.5 shows results of an unconfined compression test on a geofoam specimen of 28.8 Kg/m^3 density. The uncorrected curve has a seating error up until the strain reaches about 0.015 (1.5%) strain in front of the elastic loading region. The corrected plot was produced by removing the seating error. Strength values indicated for 1%, 5%, and 10% strain in the practice standards are obtained from corrected plots.

Table 1-2 shows the properties of currently available standard EPS geofoam types in the market. The compressive and flexural strength values increase with density. However, the oxygen index parameter is not dependent on density and remains a minimum of 24% for all available EPS types. The increasing compressive strength values obtained from unconfined compression tests on small geofoam samples are shown plotted in Figure 1.6.

Table 1-2 EPS geofoam properties from ASTM D6817/D6817M – 15

EPS Type	**Compressive Resistance at 1% strain, min., kPa (psi)**	**Compressive Resistance at 5% strain, min., kPa (psi)**	**Compressive Resistance at 10% strain, min., kPa (psi)**	**Flexural Strength, min., kPa (psi)**
EPS 12	15 (2.2)	35 (5.1)	40 (5.8)	69 (10)
EPS 15	25 (3.6)	55 (8.0)	70 (10.2)	172 (25)
EPS 19	40 (5.8)	90 (13.1)	110 (16.0)	207 (30)
EPS 22	50 (7.3)	115 (16.7)	135 (19.6)	240 (35)
EPS 29	75 (10.9)	170 (24.7)	200 (29.0)	345 (50)
EPS 39	103 (15.0)	241 (35.0)	276 (40.0)	414 (60)
EPS 46	128 (18.6)	300 (43.5)	345 (50.0)	517 (75)

Project specifications in bid documents or acquisition contracts state the required volume of EPS type and properties as in Table 1-2 and the related ASTM standards.

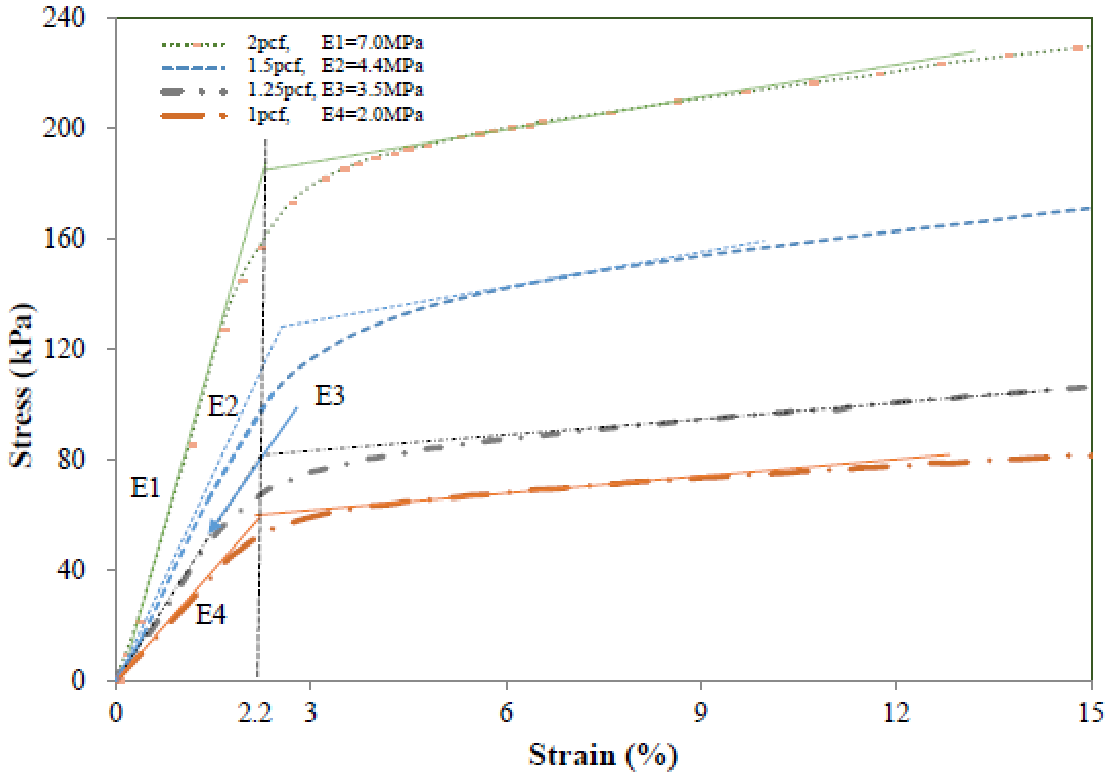


Figure 1.6 Corrected stress and strain plots for different densities of 50 mm cube EPS samples

(Liu, 2015)

1.3 Quality assurance in EPS geofoam application

Quality assurance procedures are very important in regulating the quality of EPS geofoam blocks supplied in a project. The quality assurance procedure determines the sampling and specimen collection steps as per ASTM C390 – 08 (reapproved 2013). The number of samples or specimens will depend on the lot size. For the samples selected, the weight, dimensions, and density are obtained. If the results from selected samples do not conform to the results expected, the lot may be rejected and the sampling will shift from normal to tightened inspection. As EPS block deliveries continue to meet the tightened inspection criteria, further inspections can be lowered to normal criteria in accordance with the same ASTM standard.

Engineering properties to qualify a specified EPS block type are assessed on the basis of compression and flexural strength results from testing small sized samples. Acceptance and rejection criteria for shipments delivered on site depend on weighing full size EPS blocks. Quality control and adequacy of the production plant is confirmed by third party certification and record of regulatory inspection.

1.4 The thesis elements

This thesis aims to investigate the feasibility of using Non Destructive Testing (NDT) for on-site testing of EPS geofoam blocks for quality assurance. Current quality assurance methods are reviewed. Background on NDT methods is provided. The NDT instrument for the laboratory and field tests at different EPS production plants is described. Small samples were tested in the laboratory and full blocks of different densities were tested at manufacturing plants. Results and interpretation of NDT data on EPS geofoam blocks are presented and compared with prior findings. Finally, the conclusions from the findings are presented and further areas of research are recommended.

2 Literature Review

2.1 History of EPS quality assurance measures

Quality control implies to a specific set of tools, technics, and skills through which a product inspection can be carried out against a specification; whereas, quality assurance is the general activity of collecting, gathering, and presenting evidence needed to establish a certainty that the product inspection is being effectively performed; which may include quality planning, quality control, quality improvement, quality audit, and reliability (Juran & Godfrey, 1998).

A homogenous test has been used to check the quality of an EPS block in Taiwan (Lin, Sasaki, & Chiou, 2011). Two EPS blocks that were produced in Japan and two other blocks that were produced in Taiwan were collected. The entire EPS blocks measure 2.0 X 1.0 X 0.5 m and were cut in to cubes of 10 cm dimensions and three type of tests were conducted. These were compressive strength, water absorption, and hardness tests. These tests were performed to compare the EPS quality from the two countries. The number of sample cubes prepared and tested were 2000 and 1080 respectively from the Japanese and Taiwanese blocks. Out of these, 10 and 557 cubes were respectively found to be defective from the Japanese and Taiwanese samples. It is important to note here that all ten samples that were found to be defective from the Japanese samples had a higher unit weight than the nominal unit weight for the block while six cube samples had lower unit weights from the nominal for the Taiwanese samples. Finally, it was concluded that there is still more room for improvement in the quality of the Taiwanese blocks.

Bulk density and Compressive strength testing were performed for samples taken out from an EPS geofoam block measuring 0.5 X 1.0 X 5.0 m in Sweden (Eriksson & Trank, 1991). Samples that approximately measure one fifth of the full block were used to check the density for the block. It was found that there was a 25% variability in density. From compressive tests, it was found that small samples have lowered compressive strength below 4% strain compared with large samples. Finally, it was concluded that variability in density, strain rate and sample sizes affected the compressive properties of an EPS geofoam block.

In Greece, an embankment for a highway was proposed to be constructed with the use of EPS geofoam as the lightweight fill material (Papacharalampous & Sotiropoulos, 2011). The project site had soil properties that were described as very soft clay. In addition, the construction of the highway was required to be completed quickly due to traffic issues. The highway also had a settlement restriction of under 10 cm after completion. Quality assurance checks of the EPS geofoam blocks such as dimensioning, external stability (global analysis of the whole embankment slope and foundation soil), buoyancy, internal stability (factor of safety for sliding between two blocks), and stress and deformations were checked during the design. European standards and specifications by the Norwegian Road Research Laboratory (NRRL) were mainly referred for quality control and quality assurance.

The EPS method Development Organization (EDO) in cooperation with the Norwegian Public Roads Administration (NPRA) established a standard for use of EPS geofoam in Japan (Tsukamaoto, 2011). A test highway embankment with pressure sensors was built to check the performance of EPS geofoam under actual loading conditions. EPS geofoam blocks of dimensions 2.0 X 1.0 X 0.5 m. were used in the test embankment. Having had satisfactory results, the EDO went on to standardizing material properties. Material properties such as the allowable and ultimate compressive strength, creep properties, frictional resistance, modulus deformation, and dynamic characteristics served as a quality control check for EPS geofoam while the quality assurance procedures were not clearly stated.

The first EPS geoblock road embankment in Norway was completed using a 10 cm polyurethane foam that was foamed in situ and two layers of EPS geoblocks measuring 0.5 m (Alfheim, Flaate, Refsdal, Rygg, & Aarhus, 2011). The embankment was to be located at a site with severe settlement issues which necessitated the application of light weight fill materials. The authorities required an in situ polyurethane foam property of a minimum compressive strength of 50 kN/cm^2 at a strain of 5% after a period of 24 hours of having finished. Additional requirements of maximum resistance to pulsating loads of 25 kN/cm^2 and maximum density of 100 Kg/m^3 were requested. The polyurethane was mainly required for protecting the EPS foam blocks from a possible case of petrol spill on the embankment which may dissolve the foams. For the EPS foams, a compressive strength of 50 kPa was requested. However, foams with compressive strengths of 100 kPa were used as they were the most commonly produced foams. There were no stated quality assurance measures taken in this project other than the quality control checks for compressive strength and density requirements in the design phase.

Earlier projects that involved the use of EPS geofoam mainly relied on putting forward working limits for EPS geofoam property values such as density and compression strength requirements for the blocks. From construction practices above, it can be seen that there has not been an effective quality assurance check after delivery of the blocks to the project site. Moreover, project engineers have relied more on monitoring of the EPS geofoam during the lifetime of the constructed structure.

2.2 Practice standards for EPS geofoam application

Different countries implement different standards according to their construction technology and experiences. With regards of quality control and quality assurance of EPS geofoam, many countries use similar standards or have based their own standards according to other countries' experiences. The widely used standards in EPS geofoam quality checks are discussed in this section. In the United States, the ASTM and AASHTO standards are mainly used. In addition, several State Departments for Transportation have their own recommendations on construction and quality procedures using EPS geofoam. The Norwegians, who have built the world's first ever EPS embankment (Alfheim, Flaate, Refsdal, Rygg, & Aarhus, 2011) (Tsukamaoto, 2011), have established their own standards. The Netherlands use the European Standards which has adapted some of its procedures from the Norwegian Standards. The Japanese have their own EPS standard which is also written by taking into account the results forwarded by the Norwegian Standards (Tsukamaoto, 2011).

2.2.1 American Society for Testing and Materials (ASTM)

One of the major standards used in the construction industry in the United States is the ASTM standards. ASTM D7180/D7180M – 05 (reapproved 2013) provides information on the application of EPS geofoam as it applies to geotechnical projects. This standard states the requirement for certification of EPS geofoam suppliers and sampling of the supplied geofoam according to ASTM D6817/D6817M – 15. The certification will be based on results obtained by a third party company.

Table 2-1 Sampling and acceptance criteria for quality assurance of EPS geofoam block from ASTM C390 – 08 (reapproved 2013)

Lot Size (shipping units)	**Normal Inspection**		**Tightened Inspection**	
	Sample Size	**Acceptance Number, Maximum number of Nonconforming units**	**Sample Size**	**Acceptance Number, Maximum number of Nonconforming units**
150 or less	*	*	5	1
151 to 1200	5	1	8	1
1201 to 35000	8	2	8	1
35000 and over	13	3	13	2

Note: * for less than 150 units supplied, third party certification shall be sufficient for acceptance.

The sampling procedure put forward in the ASTM C390 – 08 (reapproved 2013) is the quality assurance procedure for EPS geofoam and is shown in Table 2-1. Specific lot sizes have a standard normal and tightened inspection requirements based on acceptance and rejection from weight, dimension and density testing. A lot describes definite quantities or units that are produced under conditions of productions that are considered to be uniform. Nonconformity indicates a scenario where the selected EPS geofoam does not meet the required specification. The same standard recommends an acceptable quality level of 10% from the sampling process.

When two out of five consecutive lots are rejected the sampling process moves from normal to tightened inspection. Afterwards, when five consecutive lots are accepted, the sampling moves back from tightened to normal. If ten consecutive lots remain on tightened inspection, then the inspection process should be discontinued until quality is improved.

ASTM D6817/D6817M – 15 recommends the use of sampling procedures according to ASTM C390 – 08 (reapproved 2013) and then inspection these EPS geofoam samples on weight, dimensions and density according to ASTM D1622/D1622M – 14.

Table 2-2 Sample selection for quality control of EPS geofoam blocks from ASTM D7557/D7557M – 09 (reapproved 2013)

Initial Sampling	**Ongoing Sampling**	
1 block from the first lot	1 block per each 500 m^3 (650 yd^3) for the first 2000 m^3 (2600 yd^3)	1 block per each 2000 m^3 (2600 yd^3) thereafter

The sampling procedure indicated in ASTM D7557/D7557M – 09 (reapproved 2013) presents the quality control of EPS geofoam blocks supplied to a project and is shown in Table 2-2. From the EPS geofoam blocks sampled, specimens from three regions, which are the opposite corners and the middle part along the diagonal of the EPS geofoam and that are from areas that are not close to the surface, will be collected. The location of the three regions is shown in Figure 2.1.

The small specimens selected will be checked against the specifications provided in ASTM D6817/D6817M – 15. The main EPS geofoam properties that are checked for compliance from these specimens are the compressive strength and density. The compressive strength and density will be executed as per the procedures provided in ASTM D1621 – 16 and ASTM D1622/D1622M – 14 respectively.

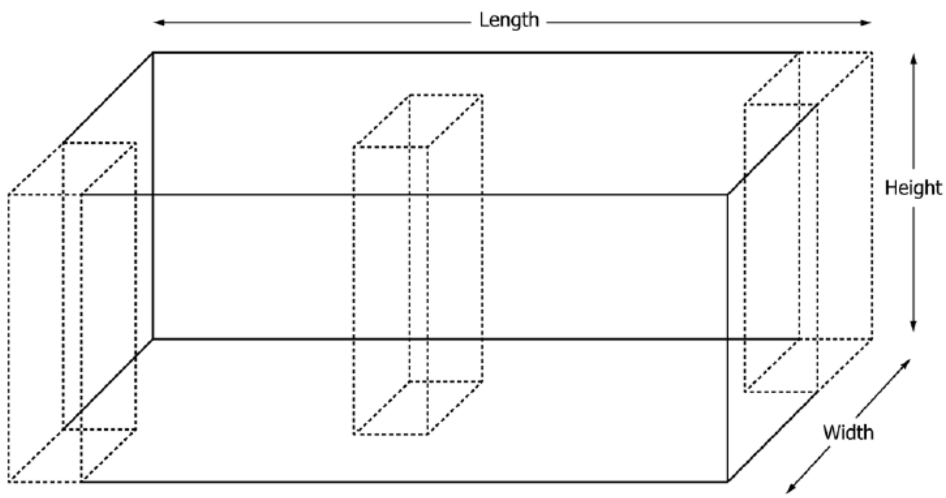


Figure 2.1 The three regions for specimen selection from ASTM D7557/D7557M – 09 (reapproved 2013)

Before undergoing tests, the prepared samples will be left to stabilize with standard laboratory temperature (23 ± 2^{0}C/73.4 ± 4^{0}F) for a period of not less than 24 hours. For the density requirement according to ASTM D1622/D1622M – 14, a minimum of three 1 cubic inch samples are prepared from various part of the sample and are weighed. Three measurements of the dimensions of the sample will also be taken and the lesser value obtained will be used. The density will then be obtained as the ratio of the weight to the volume of the specimen.

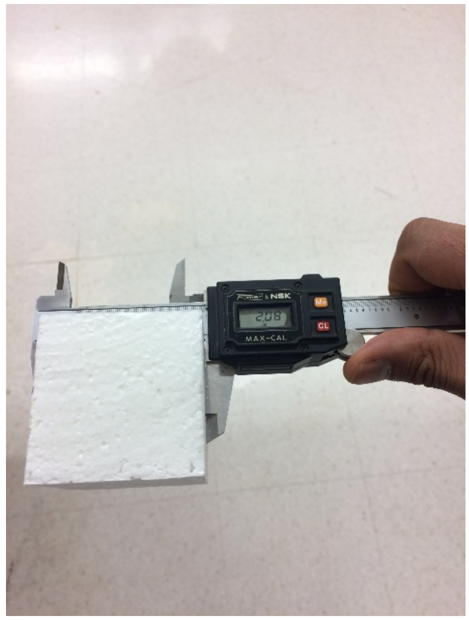


Figure 2.2 Measuring the dimensions of a specimen using a digital caliper

Testing for the compressive resistance of the EPS geofoam requires a minimum of five cube specimens each having 50 mm (2 in.) dimensions (shown in Figure 2.2) to be examined as per ASTM D1621 – 16. These specimens will go through the stabilization process as indicated above for the density test. Having completed the stabilization period, the specimens will be measured three times and an average value will be taken for their dimensions. The specimen will then be placed between the loading platens of an unconfined compression testing equipment as shown in Figure 2.3. The specimen will be placed in a way which makes it aligned to the center of the loading platens where a uniformly distributed load can be applied over the entire surface of the specimen. A strain rate controlled experiment at 10% per minute will be performed and, after performing correction for the seating error, the strength at 1%, 5%, and 10% strains can be obtained. ASTM D7557/D7557M – 09 (reapproved 2013) maintains that any individual specimen tested should not have a compressive strength less than 90% of the minimum requirement from those stated in ASTM D6817/D6817M – 15.

Figure 2.3 Sample (50 mm) setup for compression testing

ASTM D6817/D6817M – 15 also states additional testing with regards to flexural strength and oxygen index. The flexural strength and oxygen index tests are performed according to ASTM C203 – 05a (reapproved 2012) and ASTM D2863 – 13 respectively.

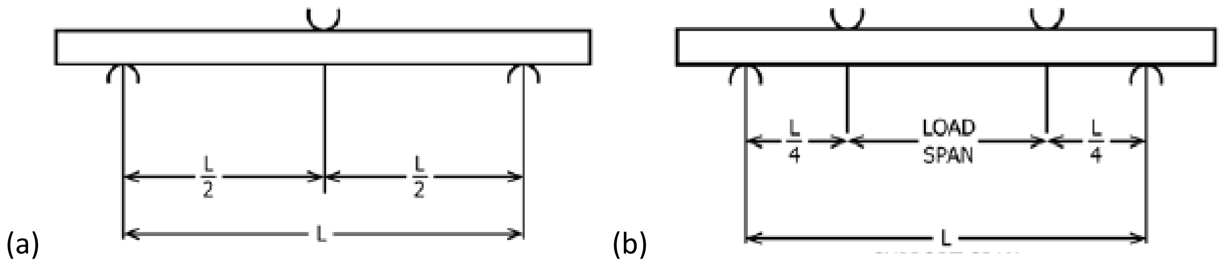


Figure 2.4 Flexural test setups as per ASTM C203 - 05a (reapproved 2012) (a) test method I (b) test method II

Figure 2.4 shows the one point (test method I) and two point (test method II) test setups for determining flexural strength for EPS geofoam. A standard size of 1 X 4 X 12 in. of EPS geofoam sample is used to check the flexural strength. The location of the maximum axial stress and bending moment differ for the two setups. The one point test represents point loading whereas the two point test simulates a uniform loading between the two loading fittings.

2.2.2 National Cooperative Highway Research Program (NCHRP)

The NCHRP has a very detailed description of quality control and quality assurance procedure for the use of EPS geofoam as a light weight fill in road embankments and bridge approach fills (Strak, Arellano, Horvath, & Leshchinsky, 2004). The NCHRP report 529 states that the responsibility for quality control for EPS geofoam is the EPS manufacturer whereas the responsibility for quality assurance is the owner’s agent unless stated otherwise by the owner.

The quality control procedure requires the EPS manufacturer to state the materials that constitute the EPS geofoam blocks i.e. whether it is made using virgin material only or regrind material was added during the production. In addition, it requires the EPS manufacturers to provide detailed information for their source of polystyrene and regrind material. The procedure specifies a minimum of 72 hour curing in room temperature and requires that enough space between blocks be provided to allow circulation of air and efficient release of residual blowing agent. The quality control also maintains the flammability requirement stated in the ASTM C578 – 16. The NCHRP report 529 specifies using only the EPS geofoam density standards recommended by the American Association of State and Highway and Transportation Officials (AASHTO). These recommended densities by AASHTO are shown in Table 2-3.

Table 2-3 AASHTO material designation from NCHRP report 529

Material Designation		**Minimum Allowable Density, kg/m^3 (Unit Weight, lbf/ft^3)**	
AASHTO	**ASTM C578 - 16**	**Full Block**	**Any Test Specimen**
EPS 40	I	16.00 (1.00)	15.00 (0.90)
EPS 50	VIII	20.00 (1.25)	18.00 (1.15)
EPS 70	II	24.00 (1.50)	22.00 (1.35)
EPS 100	IX	32.00 (2.00)	29.00 (1.80)

For test specimens, AASHTO has also put forward minimum allowable values for compressive strength, flexural strength, elastic limit and Young's modulus values and these values are shown in Table 2-4.

Table 2-4 AASHTO minimum requirements for EPS test specimens from NCHRP Report 529

Material Designation	**Dry Density/unit weight, kg/m³ (lbf/ft³)**	**Compressive Strength, kPa (psi)**	**Flexural Strength, kPa (psi)**	**Elastic Limit Stress, kPa (psi)**	**Young's Modulus, MPa (psi)**
EPS 40	15 (0.90)	69 (10)	173 (25)	40 (5.8)	4 (580)
EPS 50	18 (1.15)	90 (13)	208 (30)	50 (7.2)	5 (725)
EPS 70	22 (1.35)	104 (15)	276 (40)	70 (10.1)	7 (1015)
EPS 100	29 (1.80)	173 (25)	345 (50)	100 (14.5)	10 (1450)

Procedures for sample preparation and tests performed on specimens are to be in accordance with ASTM C578 – 16. The compressive strength and Young's modulus indicated in Table 2-4 are from tests performed at a rate of 10% strain per minute. The controlling strength is then obtained at 1% strain. With regards of quality control on dimensions of EPS geofoam block, the NCHRP states that there should not be deviations exceeding 0.5% from the nominal dimensions. In addition, perpendicular planes should stay within 0.3 cm of flexibility in a 50 cm distance and planarity should be within 0.3 cm when measured by a straightedge in a length of 3 m.

The quality assurance procedure forwarded by the NCHRP is a two phase procedure. Phase one of this procedure is performed before the EPS geofoams are shipped out to their respective projects. In this Phase, the certification of the EPS geofoam manufacturer by a third party is confirmed. If the manufacturer does not have third party certification, a minimum of three blocks for each EPS density used in the project shall be sent to the owner for testing. If a third party certification exists, the additional testing and pre construction sample submittal will be waived. EPS geofoam blocks will not be shipped to the project site before the completion of all the steps in Phase one.

As Phase one is completed, the EPS blocks will be shipped to the site. The information of each block (date of mold, weight, name of manufacturer) will be written on the block so that they can be easily identified. The agents that are responsible for the transport and storage of the EPS blocks onsite should handle them with care so to avoid damage. NCHRP recommends that the EPS geofoam blocks should be stored in an area where there will be no heat buildup. In addition, the blocks should be kept away from any flammable material and that smoking near the blocks should be forbidden.

Phase two of this procedure involves the testing of the EPS blocks when they arrive on site. Quality assurance on site takes place in four steps. The first step is a visual inspection of the transported blocks to check whether they are damaged and whether they have been marked properly with the required information. The owner should visually inspect each and every block supplied in this step; whether or not the EPS block supplier or manufacturer is third party approved does not matter. Blocks that are rejected must either be returned to the supplier or put in a separate place from the blocks that are accepted. The second step in the quality assurance procedure is checking whether or not the density and dimensional requirements of the EPS blocks are met. For an EPS geofoam supplier that has a third party certification, one block per truckload should be checked. However, for a supplier that does not have a third party certification, each block for the first truck load must be checked. The number can then be reduced to at least one block for the proceeding truckloads. If the selected block is rejected then additional blocks from the same truckload shall be used if they satisfy the requirements. If the selected block is accepted, then the contractor can be allowed to proceed with the placement of the blocks until the results from additional tests from the third step of the quality assurance measure are provided.

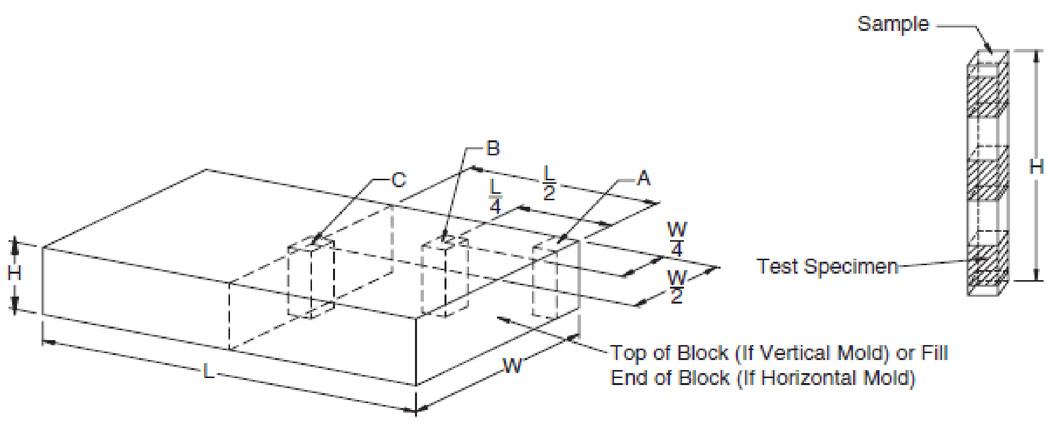


Figure 2.5 The sample collection location from NCHRP report 529

In step three of the quality assurance procedure, the strength properties of the EPS blocks that are sent to the site are checked. For suppliers that do not have third party certification, one block shall be selected for testing from the first truck load for each density used. However, additional sampling may be done at a rate of one sample per 250 cubic meters. The tested specimens will be then checked against the AASHTO properties for EPS geofoam listed in Table 2-4. Specimens are collected as per Figure 2.5. If unsatisfactory results are obtained from this step, the contractor will be asked to remove the placed EPS blocks and replace them with accepted blocks at its own expense. The last step in the quality assurance procedure is the preparation of the as-built drawings of the EPS blocks used in the project with their respective information and locations.

2.2.3 State Departments of Transportation

The United States Department of Transportation (USDOT) is a federal organization that is responsible for transportation and transportation related matter. In addition to the USDOT, all States have their own departments that deal with transportation related matters. All State DOTs have their own guidelines when it comes to construction of highways and embankments and in turn their own material quality control and quality assurance measures. For the use of EPS geofoam, the New York State, Utah, Michigan, Virginia, and Minnesota State Departments of Transportation have provided quality assurance and quality control recommendations.

New York State Department of Transportation (NYSDOT) has a brief quality control and quality assurance program with regards to construction using EPS geofoam as a light weight fill (NYSDOT: Geotechnical Engineering Manual - 24, 2015). NYSDOT requires a third party to assess and perform quality control procedures used by the EPS geofoam supplier before beginning work. The EPS geofoam supplier is given a minimum of 20 days before starting work to produce documents pertaining to its third-party certification testing on two EPS blocks which were produced within 6 months of the project start date. Having shown proof of certification, the next stage will be sampling and testing. The NYSDOT recommends using ASTM D1622/D1622M – 14 and ASTM D1621 – 16 for testing the Density and Compressive properties respectively of the EPS block. For specimen preparation, a random EPS block will be selected and three square areas of 35 X 35 cm (14 X 14 in as shown in Figure 2.7) dimensions will be marked out (NYSDOT:

Geotechnical Testing Program - 7, 2015) at locations indicated in Figure 2.1. These three areas should be marked on an undamaged block. NYSDOT specifies a 22 gage NiCr (Nickel Chromium) cutting hot wire to be used to cut the long and short sides of the EPS block. For the short side, a 3 ft. wire with 6 volts, 3 ohms and 2 amps, where as a 6 ft. wire with 14 volts, 6.5 ohms and 2 amps is recommended for the longer side (NYSDOT: Geotechnical Testing Program - 7, 2015). The columns will be cut and the top and bottom sides will be marked to maintain orientation.

Figure 2.6 Three columns of 35 X 35 cm (14 X 14 in.) extracted from an EPS block with horizon markings *(NYSDOT: Geotechnical Testing Program - 7, 2015)*

Having obtained the three columns from an EPS block, NYSDOT requires three horizons to be marked on the columns as shown in Figure 2.6**.** One specimen will be collected from the three horizons, upper, middle and lower, of each column making it a total of nine specimens. The horizons must be more than 7.5 cm further from the top and bottom face of the columns. The cube specimens cut out from the horizons should have dimensions of 9 cm. Finally, by using a precise hot wire trimming instrument, the final 5 cm dimension cubes will be prepared for density and strength test. It is required that the information of the cubes such as source horizon and orientation is kept.

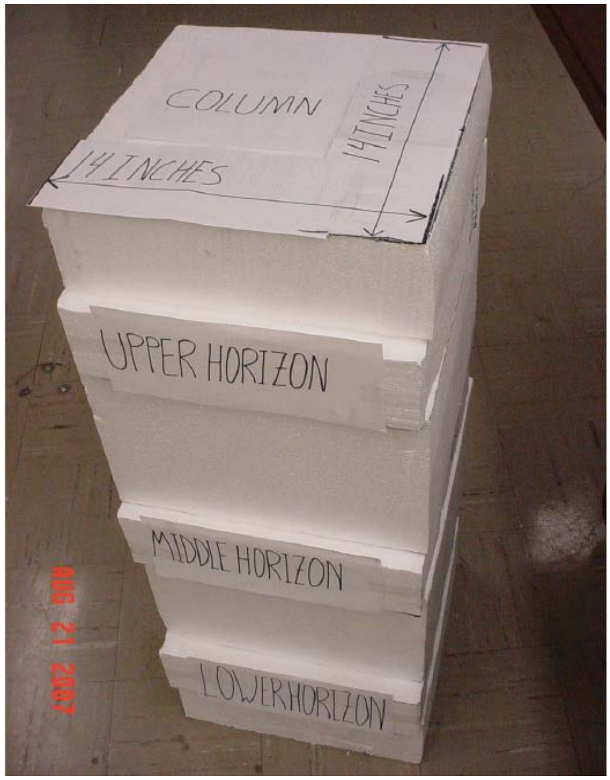


Figure 2.7 Upper, middle and lower horizons

NYSDOT also recommends a quality assurance procedure which starts with the engineer checking the density of the transported EPS geofoam blocks on site. One block from either a truckload or 70 cubic meters of blocks transported must be checked. The contractor in this case is expected to provide a certified weighing scale for the engineer which is within 0.05 kg accuracy. The transported blocks must be labeled with the manufacturer's name, type, density, resin source, lot number and date of molding. NYSDOT reserves the right to retain a randomly selected block for additional testing. If the tests result in unacceptable values, the contractor will be told to remove and substitute the placed EPS blocks. The quality assurance procedure also states that an EPS block should be rejected if it exceeds a dimensional tolerance of 0.5% and a ratio of surface damage area to side area of more than 20% or a ratio of damaged area to block volume of more than 1%. The procedures taken to obtain strength and additional properties are according to the ASTM standards and are summarized below.

Table 2-5 The NYSDOT minimum requirements for EPS block *(NYSDOT: Geotechnical Engineering Manual - 24, 2015)*

Unit Weight, kN/m^3 (pcf)	**Compressive Strength, kPa (psi)**		**Flexural Strength, kPa (psi)**	**Flammability (Oxygen index)**
	1% deformation	**10% deformation**		
0.2 (1.25)	40 (5.8)	110 (16)	207 (30)	24%

Minnesota State Department of Transportation (MNDOT) also specifies a very short and concise quality control and assurance criterion (MnDOT: Office of Materials Engineering, 2007). The recommendation by MNDOT specifies a visual inspection of the supplied block. The visual inspection asks for a check of color change (yellow aged material), dimensional requirements and consistency of material used. It also requires checking the density of a cube sample with a dimension of 0.3 m. One sample shall be collected for every 35 blocks.

2.2.4 European standards

Even though the quality control and quality assurance procedures recommended by the European Standards are implemented across Europe, certain countries still continue to use their own standards with EPS geofoam applications. Quality assurance for EPS geofoam in the

European standard requires the EPS geofoam block supplying company to produce documents that show the strength, dimensional and material composition and consistency requirements are maintained during production. Information regarding the flammability properties of the EPS geofoam supplied may also be required (Frydenlund, et al., 1997). It also states that sample tests by the authorities should be completed 3 – 5 days before prior to EPS geofoam placement date.

Table 2-6 Sample collection rate for strength check *(Frydenlund, et al., 1997) (Norwegian Directorate of Public Roads/Road Research Laboratory, 1992)*

EPS fill size m^3	**Minimum number of blocks Tested**
<500	3
500 – 1000	5
>1000	5 per 1000 m^3

The European Standards recommend the selection of samples according to Table 2-6 for strength tests. For dimensional and evenness tests, an average of 1 per 25 blocks are recommended for testing and a minimum of 10 samples are required to be tested in any delivery. Samples are also recommended to be left to cure for a minimum of 6 hours.

Six specimens are collected from a sample block as shown in Figure 2.8. The standard recommends the drying of the cubic 5 cm specimens in an oven at a maximum temperature of 50 ^{0}C and then cooling them before performing weight and dimensional measurements. The

European Standard (European Comittee for Standardization, 2001) provides the compressive strength requirements for EPS geofoam under 2%, 5%, and 10% deformations. The compressive strength of the specimens are recommended to be checked and compared at a 10% strain rate testing. The standard also suggests an average method of taking dimensions of the sides of the full block by taking the average of two edges and the middle of the face. The measured side should be within 0.05 cm accuracy from the standard. The flammability of the block is suggested to be checked according to the ASTM D2863 – 13. In Figure 2.8, the height (H) and width (B) of the block shall measure a minimum of 0.5 m while the length (C) of the block shall have a minimum length of 2.5 m (Frydenlund, et al., 1997).

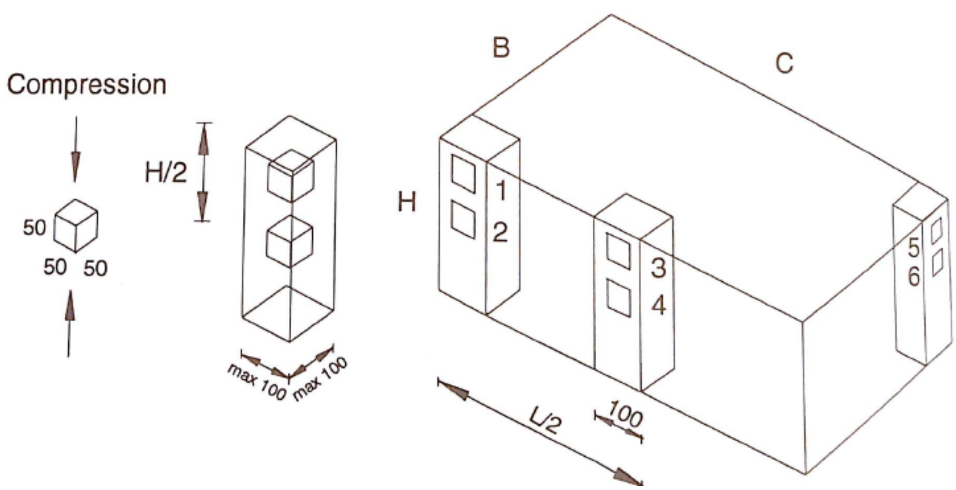


Figure 2.8 The European standards specimen collection location (measurements are in mm) *(Frydenlund, et al., 1997)*

A specific block labeling criteria by the European Standard includes the product name, address of the manufacturer, year and time of production, reaction to fire class, nominal thickness, length and width, and facing property.

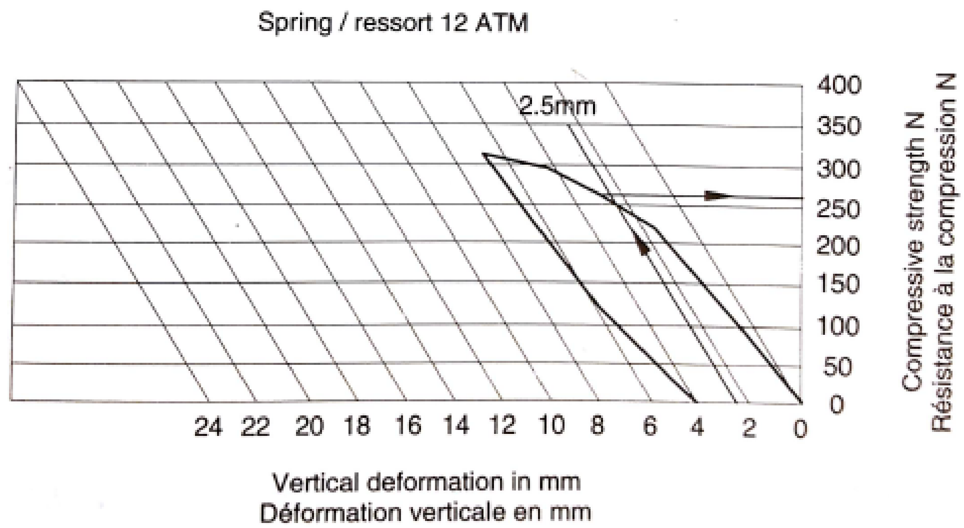


Figure 2.9 Stress strain plot in the Norwegian and European standards *(Frydenlund, et al., 1997)* *(Norwegian Directorate of Public Roads/Road Research Laboratory, 1992)*

The quality control standard suggests implementation of a direct and indirect method of testing. The direct method is the method of testing suggested by the standard itself and the indirect method relies on the manufacturer's own relationship derived or other correlations that may be derived from the results obtained from the direct method and apparent density of the EPS block tested. According to the direct method, the dimensional requirements of the full EPS geofoam block are to be checked once every two hours of production and the flatness is to be checked once every eight hours.

The Standard has a more relaxed procedure when it comes to checking the compressive and bending strengths of EPS geofoam. The standard suggests testing of compressive strengths at any of the deformation stages at a rate of one per day, one per three months or one per year and the bending strength at a rate of one per day or one per three months using the direct method. Both the compressive strength at 10% deformation and bending strength are used in classifying the EPS blocks. Table 2-7 summarizes the different classes of EPS geofoams according to the European Standard with their respective compressive and bending strengths.

Table 2-7 Classes of EPS geofoam and strength properties *(European Comittee for Standardization, 2001)*

Type	Compressive strength at 10 % deformation, kPa (psi)	Bending strength, kPa (psi)
EPS 40	40 (5.8)	60 (8.7)
EPS 50	50 (7.3)	75 (10.9)
EPS 60	60 (8.7)	100 (14.5)
EPS 70	70 (10.2)	115 (16.7)
EPS 80	80 (11.6)	125 (18.1)
EPS 90	90 (13.1)	135 (19.6)
EPS 100	100 (14.5)	150 (21.8)
EPS120	120 (17.4)	170 (24.7)
EPS 150	150 (21.8)	200 (29.0)
EPS 200	200 (29.0)	250 (36.3)
EPS 250	250 (36.3)	350 (50.8)
EPS 300	300 (43.5)	450 (65.3)
EPS 350	350 (50.8)	525 (76.1)
EPS 400	400 (58.0)	600 (87.0)
EPS 500	500 (72.5)	750 (108.8)

2.2.5 Norwegian Directorate of Public Roads/Road Research Laboratory

The Norwegians are believed to be the first use EPS geofoam and to be present their own working standards. As a result, most of the procedures in the European standards for EPS geofoam were taken from the Norwegian standards. The Norwegian standards set the minimum compressive strength of an EPS block to be used in road embankment to be 100 kPa (14.5 psi) unless other requirements are specified (Norwegian Directorate of Public Roads/Road Research Laboratory, 1992). EPS geofoams recommended for use by the Norwegian standards have compressive strengths of 100 kPa (14.5 psi), 140 kPa (20.3 psi) and 180 kPa (26.1 psi). The quality assurance in the Norwegian standards describes that the compressive strength used in design is the strength measured at 5% strain in an unconfined compression experiment performed at 10% strain rate on a cubic specimen of 5 cm size. The stress strain plotted is shown in Figure 2.9. A minimum of 6 specimens are tested for strength checks and the average values must be greater than 90% of the nominal recommended strength. In addition, all strengths obtained should be greater than 80% of the nominal strength. The sample location in the EPS block are according to Figure 2.8 and the sections of specimens collected from these samples are shown in Figure 2.10. It is important to note here that the European Standards adapted this procedure from the Norwegian Standards. The samples taken out from the block are cut using a fine toothed saw or heated wire. The standards also require the specimens to be oven dried at 50^0C for a period of 1 – 3 days before testing.

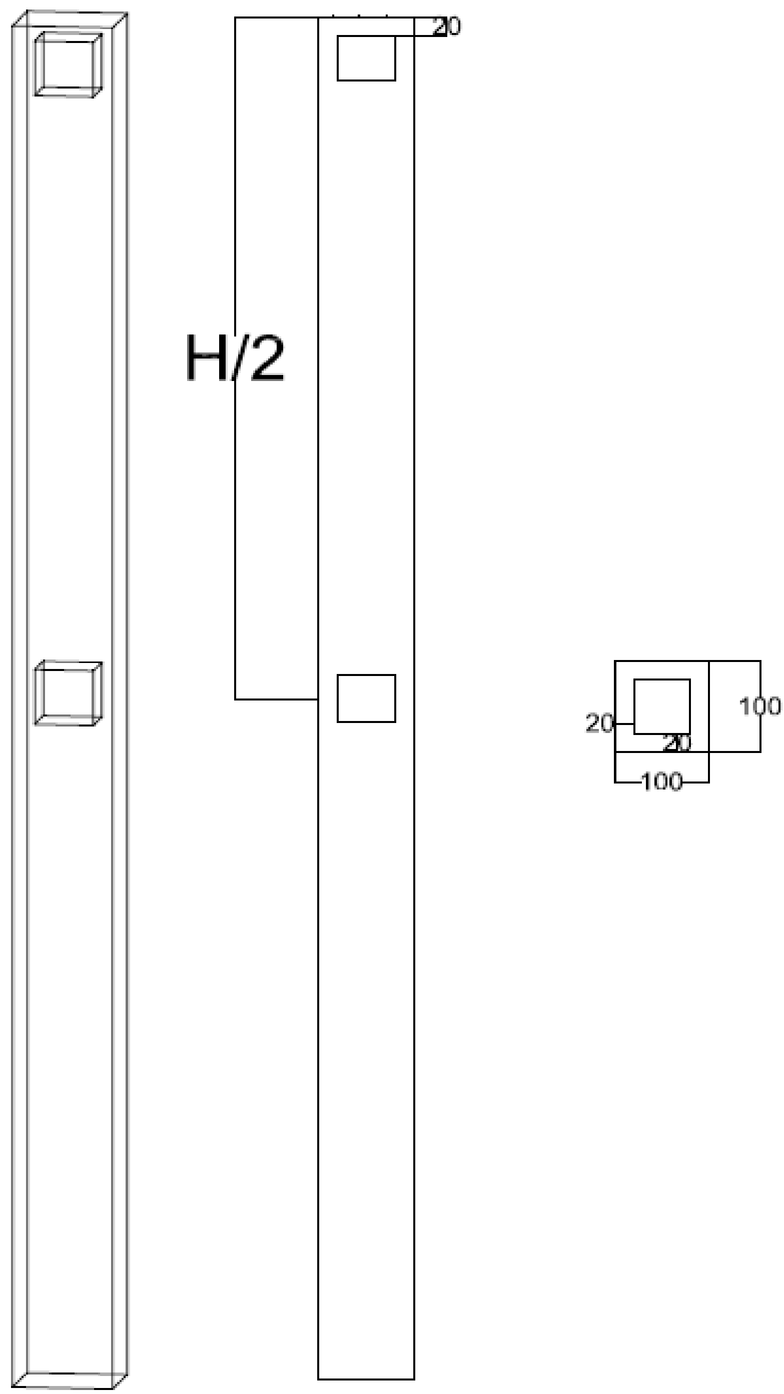
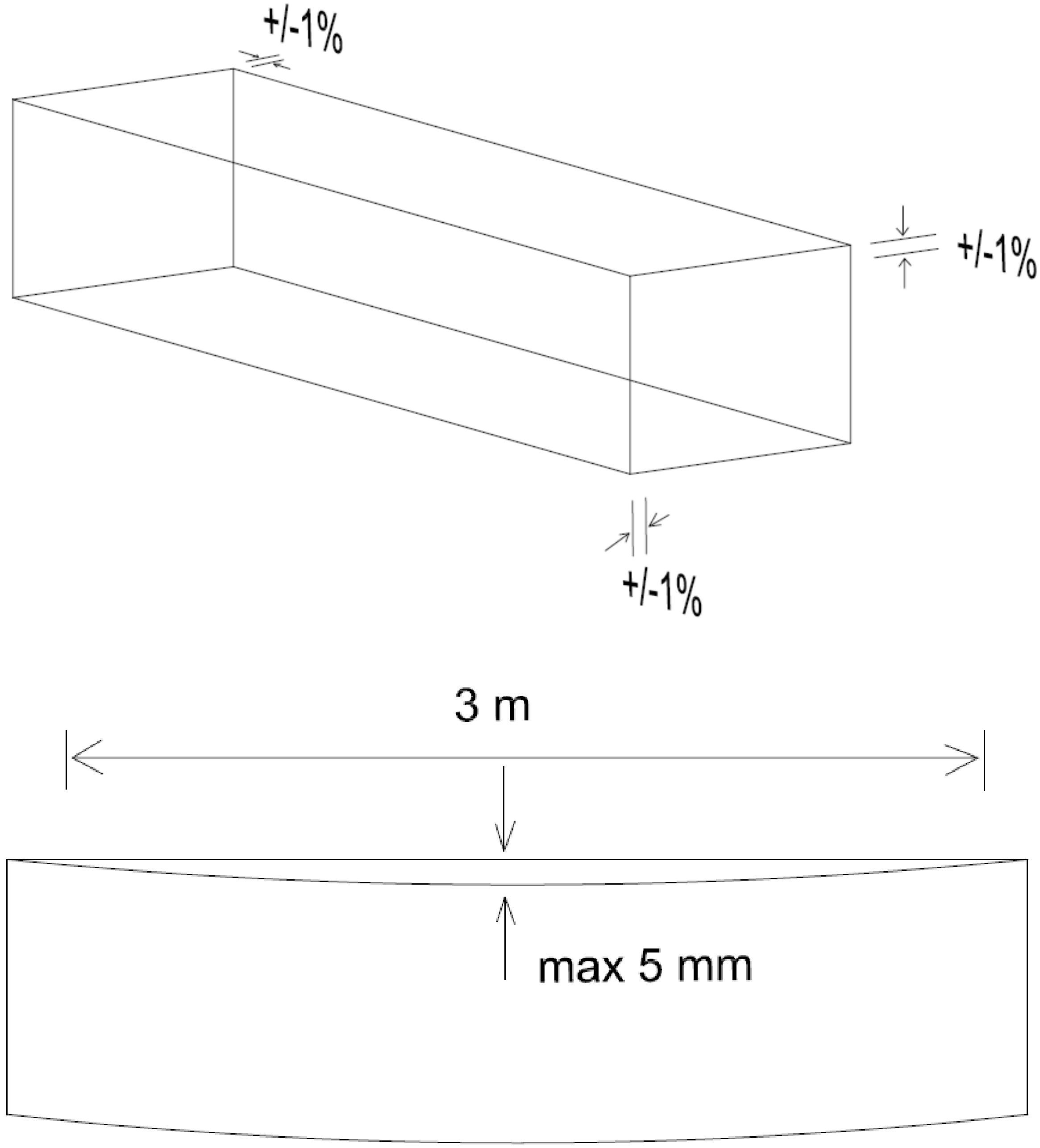


Figure 2.10 Specimen plan and side sections (measurements are in mm) *(Norwegian Directorate of Public Roads/Road Research Laboratory, 1992)*



(a) (b)

Figure 2.11 Dimensional requirements by the Norwegian Standards (a) dimensional requirements (b) evenness requirements *(Norwegian Directorate of Public Roads/Road Research Laboratory, 1992)*

The dimensional requirements state that the smallest and longest EPS block dimensions should be at least 50 and 250 cm respectively. A tolerance of 1% is allowed with regards to dimensions in the standards. Flat surfaces may have a maximum deflection of 0.5 cm when measured by a 3 m straightedge. With regards to flammability requirements, the Norwegian standards recommend testing according to ASTM D2863 – 13. The testing frequency differs for each kind of EPS property required. The compressive strength testing of samples should be according to Table 2-6. The dimensional testing frequency of EPS blocks is one block per twenty five blocks supplied. However, a minimum of 10 blocks should be tested in any delivery according to the Norwegian Standards.

With the submission of tender documents, the production quality control measures in the Norwegian standard requires manufacturers to submit documentation related to material strength, block dimensions and type and proportions of raw material used for the molded EPS geofoam blocks. Additional documentation on the flammability properties and tests performed may be required depending on the application of the EPS geofoams.

2.2.6 Japanese standards

The Japanese EPS method Development Organization (EDO) was established to promote the use of EPS in Japan (Tsukamaoto, 2011). EDO has since then developed working standards for EPS geofoam. This standard describes the geometry, density, compressive strength and fire resistance as the four areas where quality control should be mainly focused.

The quality assurance program recommends collection of EPS geofoam samples from blocks that are delivered to a project site as shown in Table 2-8. The specimen retrieved from the collected samples is also shown in Figure 2.12.

Table 2-8 Recommended sample collection by the Japanese standard *(EPS-EDO, 2014)*

EPS fill size, m^3	**Minimum Samples Recommended**
<2000	2
2000 – 5000	3
5000 – 10000	4
>10000	1 block every 2000 m^3

The compressive properties of EPS geofoam as indicated by the Japanese standards requires the application of a strain rate of 10% per minute on a cube specimen that has dimensions of 5 cm. The controlling strength is then the compressive strength measured at 10% strain and the allowable strength will be half of the strength. Regarding nomenclature of blocks, the Japanese standard offers a different naming system from ASTM. The following table summarizes the unit weight and compressive strength of EPS geofoam as per the EDO.

Table 2-9 EPS geofoam properties considered by EDO *(Tsukamaoto, 2011)*

Properties	**EPS geofoam type**				
Type	**D-30**	**D-25**	**D-20**	**D-16**	**D-12**
Unit Weight kN/m^3 (pcf)	0.30 (1.91)	0.25 (1.59)	0.20 (1.27)	0.16 (1.01)	0.12 (0.76)
Allowable Compressive stress kPa (psi)	90 (13.1)	70 (10.1)	50 (7.3)	35 (5.1)	20 (2.9)
Compressive Stress at 10% strain kPa (psi)	180 (26.1)	140 (20.3)	100 (14.5)	70 (10.2)	40 (5.8)

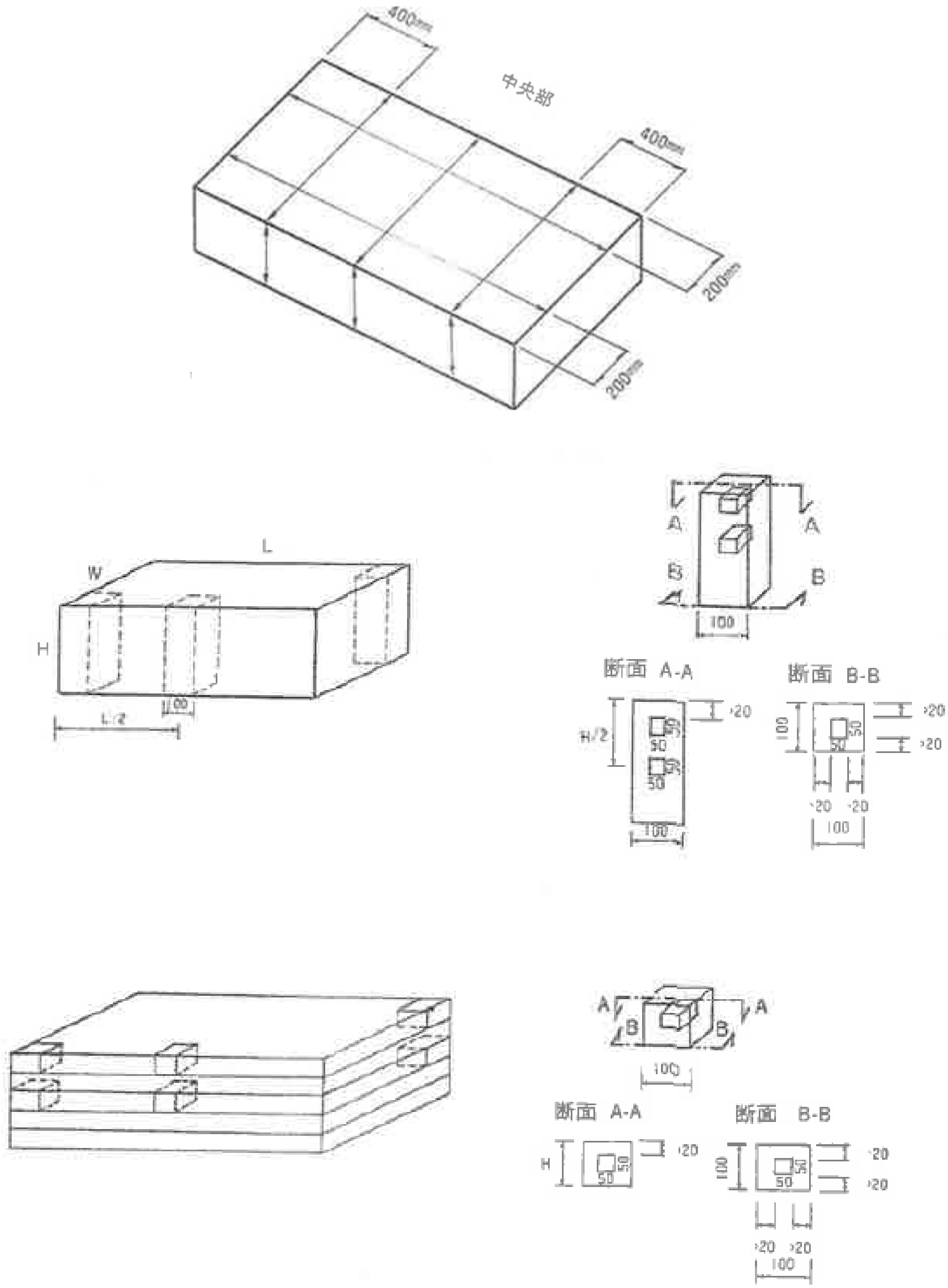


Figure 2.12 Specimen collection as per the Japanese Standards (units are in mm) *(EPS-EDO, 2014)*

2.3 Case studies

2.3.1 Buffalo Road Bridge in Oatka Creek

The Buffalo road bridge across Oatka Creek in Warsaw, NY is an excellent example of the implementation of quality assurance (Negussey, 2004). Density checks were performed on site upon delivery of the EPS blocks and all of the initial delivery was returned. Two truckloads of new replacement blocks were supplied. The new blocks were inspected and accepted on delivery. Two 1.0 X 1.2 X 1.2 m sized block samples from both the rejected and accepted samples were provided to the Geofoam Research Center for further testing. Cube sample sizes of 50, 150, and 300 mm were cut out of the provided blocks and compression tests were performed as per the ASTM D1621 – 16. Densities of test samples were in agreement with the block densities that were determined on site. Samples from the rejected blocks were below the specified density. Samples from the accepted block met the specified density for the project.

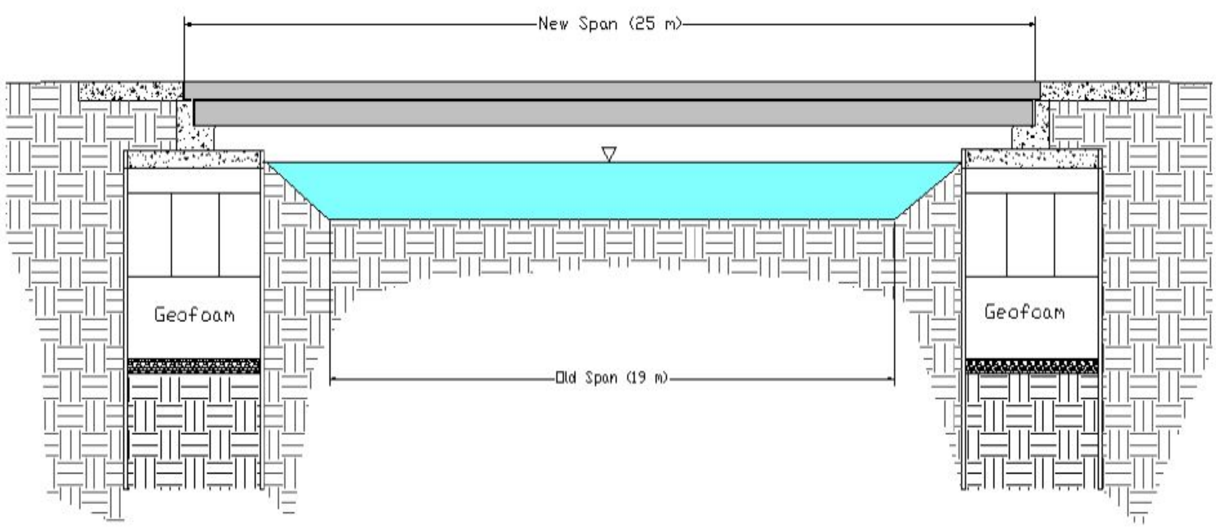


Figure 2.13 Use of geofoam at the Buffalo road bridge at Oatka Creek *(Negussey, 2004)*

From the compression tests, it was found that the rejected samples, other than having a lower density from the accepted limit, had a lower strength value than what is required by the ASTM D6817/D6817M – 15 at a 10% strain. However, the strength levels recorded for the rejected samples at 1% strain was in the acceptable margins. For the accepted samples, the density and strength values at 10% and 1% strain were all above the acceptable margin. In addition, flexural tests were performed on samples of sizes 2.5 X 7.5 X 30.5 cm and 2.5 X 10.0 X 30.5 cm collected from both the accepted and rejected samples according to the ASTM D6817/D6817M – 15 and both samples exceeded the acceptable margin for flexural strength.

2.3.2 Interstate 88 over Carrs Creek

In June 2006, a wide culvert beneath Interstate 88 at Carrs Creek failed following a severe storm. Because I88 served an average daily traffic of 11150, a rapid replacement construction schedule was mandated. To meet the completion deadline, standard pre-cast concrete culvert sections were used. Furthermore, to reduce the overburden pressures on the culvert, geofoam back fill was specified and a total of 819 blocks were supplied to the project.

Figure 2.14 Geofoam joints and differential settlement at Carrs Creek *(NYSDOT, 2007)*

The newly constructed interstate on geofoam at Carrs Creek settled 18 inches within 4 months (Negussey, Birhan, Liu, Singh, & Andrews, 2014). At this point, the geofoam supplier was asked to supply two geofoam blocks of the specified density for the Carrs Creek project. In October 2006, drillers were tasked to recover cored samples of geofoam for further testing and comparison with the new blocks provided by the supplier. In December 2006, block samples of geofoam were recovered from a test pit excavation as shown in Figure 2.15. By June 2007, all EPS geofoam blocks placed in the I88 reconstruction along the outer side slope of I88 were replaced by lightweight aggregates.

Figure 2.15 Block sampling of geofoam from a test pit along I88 *(NYSDOT, 2007)*

From the tests performed, the densities of the exhumed geofoams and cored samples met the specification of the project. However, all tested samples showed lower strength values at 1% strain from those indicated in the ASTM D6817/D6817M – 15. The tested samples also showed physical properties that hinted a possibility of high regrind content in the supplied EPS geofoam blocks. Other factors such as: excessive loading, lack of internal drainage, and continuous joints between geofoam blocks as shown in Figure 2.14 were not considered (Negussey, Birhan, Liu, Singh, & Andrews, 2014). NYSDOT specifications did not have a criterion for stress at 1% strain at that time.

2.4 Implementations of the practice standards

From the Buffalo bridge project it can be seen that the density and the strength at 10% strain had a clear correlation; whereas there was not any relationship between density and the strength at 1% strain for the rejected samples at the Interstate 88 Carrs Creek project. The results from both case studies show the importance of performing tests to determine the strength properties of EPS geofoams, in addition to density checks. The quality assurance and quality control standards (ASTM C390 – 08 (reapproved 2013) and ASTM D7557/D7557M – 09 (reapproved 2013) respectively) are not referred to by clients in EPS application projects. The values provided in ASTM D6817/D6817M – 15 are the main requirements usually in most projects.

The practice standards present quality assurance and quality control procedures which are important in describing the important parameters of EPS geofoam. The project reports of the two case studies showed that a density and strength inspection was only used in the Buffalo Bridge before the project was started while there wasn't any inspection implemented for the Interstate 88 over Carrs Creek project. Failure to adhere to the quality control and quality assurance procedures put forward by the practice standards was detrimental to the Interstate 88 project.

2.5 Limitations of the practice standards

From the practice standards discussed in this chapter, a complete quality assessment may result in a significant amount of time and money to be spent. In addition, the selection of small specimens for strength checks creates uncertainty in representing the properties of the whole block. Six specimens cut out as recommended by the standards represent about 0.01% of the block by volume. Issues such as the use of inconsistent material, such as regrind material during EPS manufacturing, affect the properties of the EPS geofoam. EPS block manufacturers may also manipulate the composition of the block by using a denser material at one location and a lighter material at another location. Even though the block attains the proper density, the strength properties may be less than those specified by the different standards. The naming, working strength limit, and EPS type produced in different parts of the world vary as seen in the practice standards. This may create ambiguity when specifying an EPS density during design.

Taking into account the sample size, cost, time, and issues that may arise from using different standards, a more effective and global means of checking material quality, in terms of homogeneity and strength, should be implemented. A quality assurance procedure that can be performed on site, can measure EPS block homogeneity and strength, and that saves time and cost will be advantageous for the client.

3 Research Methodology

3.1 Non Destructive Testing (NDT) methods

EPS geofoam is a lightweight cellular solid. The word cellular is derived from the Latin word *"cellarium"* meaning a cluster of cells (Gibson & Ashby, 1988). EPS geofoam blocks consist of a collection of fused pre puffs as shown in Figure 3.1.

Figure 3.1 EPS geofoam sample comparison of exterior skin and interior section

Depending on the constituent material and foam type (i.e. open celled, closed celled or a combination of both) the property of the cellular material varies from the solid material. Hence, an important property of cellular solids is the relative density, which is the ratio of the density of the cellular material to the solid form of the material (Gibson & Ashby, 1988). An NDT that can be used on site would be convenient and practical for quality assurance confirmation on delivery.

Bender element testing was employed to determine the elastic properties of geofoam (Sivathayalan, Negussey, & Vaid, 2001). P waves were triggered through a sample to obtain a range of Young's moduli of a sample by using bender elements. Two sets of P – wave frequency ranges, 350 – 500 Hz and 500 – 2000 Hz resulted in moduli of 17 MPa (2466 psi) and 26 MPa (3771 psi) respectively, for a 20 Kg/m^3 (1.25 lb/ft^3) density small sized sample. An upper bound value for the Young's modulus, which exceeds formerly reported for this density of EPS geofoam, value was obtained. However, the authors suggested further study of the apparent wave travel time dependency on the frequency. It is important to note here that these tests were conducted on small sized samples.

Bhaskar has also observed relations between wave velocity in a cellular material and a solid of the same material (Bhaskar, 2009). Two topologies; stretching dominated and bending dominated, were studied. For stretching dominated cellular solids, the velocity of the cellular solid was 0.58 times the velocity in solid of the same material. This relation is key in formulating a relation for the Young's moduli of the solid and cellular material.

Small strains in geofoam have been measured by making use of a Multi-Channel Analysis of Surface Waves (MASW) (Kafash, Arellano, Hosseini, & Pezeshk, 2013). Geophones were placed at intervals, as shown in Figure 3.2, on a full sized geofoam block (0.96 X 1.22 X 7.32 m) of 20 Kg/m^3 (1.3 lb/ft^3) density. A tennis ball, used as trigger or source, is dropped from a height of 15 cm at 48 different locations and surface wave measurements were taken. By dispersion and inversion analysis, the researchers determined shear wave velocities from surface waves. The shear wave velocity profile along the line of the geophones was plotted from the recorded time history. A shear modulus of 12 MPa (1770 psi) was obtained. The main drawback for using this system is that it is sensitive to surrounding vibrations. Ambient vibrations may introduce errors in readings and hence this method should be implemented in a controlled environment.

Figure 3.2 EPS geofoam NDT using Geophones *(Kafash, Arellano, Hosseini, & Pezeshk, 2013)*

3.2 Background theory

Quality assurance is important in the use of EPS geofoam in construction. Current quality assurance methods are impractical and are not used often. NDT methods present a means where more EPS geofoam blocks can be tested. NDT methods can also serve as supplementary to the existing standards. NDT methods that involve transmission of mechanical energy through a sample can help in establishing elastic properties of the EPS block. Specifically in this thesis, compressional waves, P waves, were used to determine the compressional characteristics of EPS geofoams of different densities. Properties such as the Young's modulus and Poisson's ratio of the block can be determined. The modulus values can then be used to perform a strength check by predicting the strength of the EPS geofoam and then by comparing them with values provided in the various practice standards. In addition, the consistency of the P wave velocity through the EPS block can be used to check the homogeneity of the block.

3.3 NDT instrument

The V – Meter Mark IV used in this experiment (shown in Figure 3.3) is made by James instruments Inc. The V – Meter triggers and records the travel time of ultrasonic pulse waves through a test material of given dimensions. It has an advanced level of analysis capacity which can analyze both P and S waves, compressional and shear waves, respectively. This instrument has a digital clock of 10 MHz and can measure travel times of up to 6.5 milliseconds with a 100 nanoseconds resolution. In addition, the V – Meter has a rechargeable battery and is portable which makes it suitable for on-site testing of materials. When fully charged, the V – Meter works for up to 4 hours. The V – Meter has a capacity of saving 1800 tests on its memory. An LCD screen is used to display available options in the V – Meter instrument.

Figure 3.3 The V – Meter Mark IV

The V – Meter has been used to determine non homogeneity in concrete and wood (James Instruments, 2012). Presence of voids, crack depth detection and strength estimation are also additional applications for the V – Meter (James Instruments, 2012). The transducers that come with the instrument consist of piezo-electric elements. These elements are installed in a stainless steel protective housing, and are suitable for rough site conditions. When triggered, piezo-electric elements oscillate at their natural frequency generating mechanical energy. Different transducer frequencies are available from James Instruments. These range from 24 kHz to 500 kHz for using on larger aggregates (softball sized) to ceramics and glass, respectively. These transducers are connected to the V – Meter using cables, as shown in Figure 3.4. Adequate signals can be obtained without using pre-amps for cables of up to 23 m.

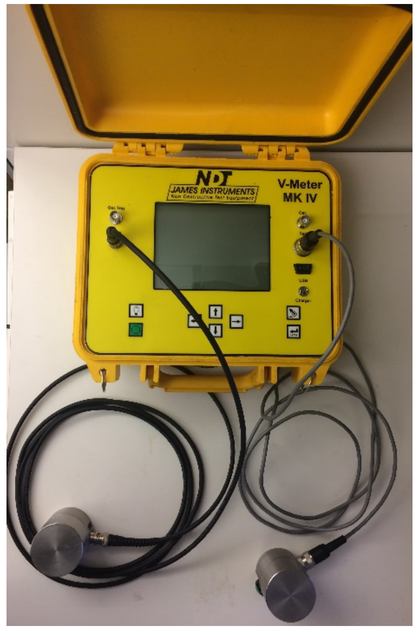


Figure 3.4 The V – Meter connected to transducers

The trigger and receiver transducers can be positioned on the surface of the test material in three different ways as shown in Figure 3.5. For direct transmission (a), the transducers are used in opposite faces of the material. The semi – direct method (b) uses the transducers in adjacent faces of the material. Lastly, the indirect method applies the transducers on the same face (c). The indirect method is preferably used for crack depth detection in materials. Among these three methods, the direct transmission method is most the sensitive as the receiving transducer receives the maximum energy. A coupling agent which mainly constitutes of petroleum jelly is applied on the transducer surface for effective transmission and reception of signals. Medium bearing grease such as silicon grease or even liquid soap can be used for smooth surfaced materials whereas pump grease or petroleum jelly should be used for rough surfaces. The data collected can then be uploaded to a PC for analysis using the Velocilinx software. The software can also be used to remotely control the V – Meter.

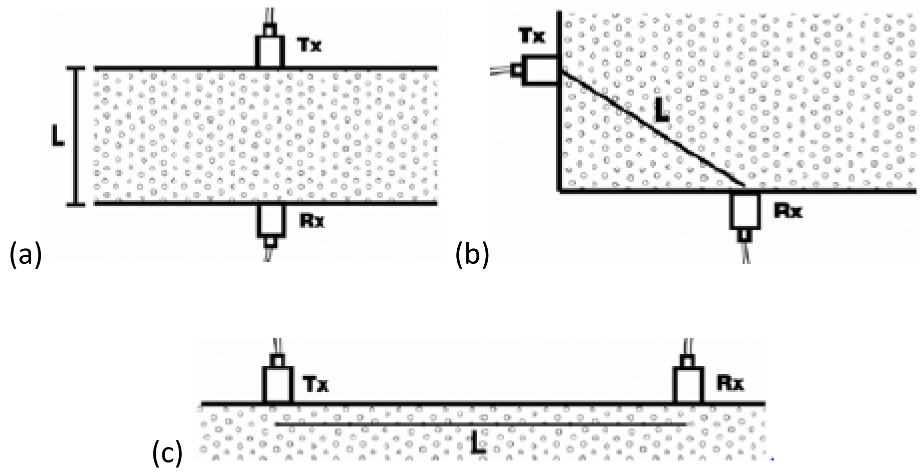


Figure 3.5 Different ways of using the trigger (Tx) and receiver (Rx) transducers across the length (L) of a material (a) direct method (b) semi – direct method (c) indirect method *(James Instruments, 2012)*

In initiating testing, the V – Meter requires the input of several test options. Pulse per sequence is an option the instrument provides that defines how many pulses will be sent in one test. The measurement mode provides choices on what kind of data is going to be collected from the experiment. The V – Meter can generate both S and P waves, hence it can measure velocity when the distance is given for both waves. The V – Meter provides a graphic representation of the wave transmission through the material during the experiment. Multiple levels of amplifier gains are available for the signal ranging from a minimum of 1 to the maximum of 500. The V – Meter also allows the selection of material density for modulus and Poisson's ratio calculations. The material density entries are in the range of 800 – 2400 Kg/m^3 (50 – 150 lb/ft^3). Hence, for EPS geofoam testing, the velocity result obtained will be used to calculate the modulus for the block using theoretical relations.

3.4 NDT method for EPS geofoam

When turning on the V – Meter, the testing menu shown in Figure 3.6 below appears immediately. The test menu presents the editable options for the specific test. The letters HV next to the test menu, on the first line, indicate the selection of High Voltage for the pulse wave in the set up menu. The “OFF” status in the second line implies the test is not yet active and then the number of pulses, of either 1, 3, or 10, being sent over a specific period of time, from 1 to 10 sec, are shown. On the third line, it indicates the test number and the SAVE ON/OFF function which shows that the test will be saved in the memory of the V – Meter. The fourth line indicates whether or not the graph of the wave should be plotted during testing. The fifth line shows the measured distance. It shows P (S) – Distance being set and the test will predict the P (S) – Velocity as shown in the next line. On the bottom of the test menu, the two lines indicate the current battery life of the V – Meter and information of manufacturing company with the date and time of the experiment.

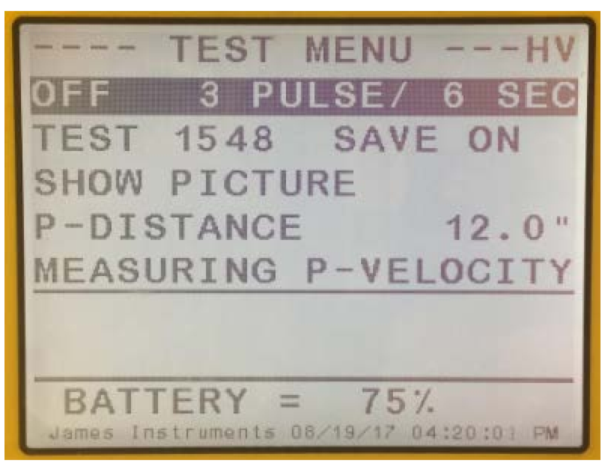


Figure 3.6 Test menu screen on the V – Meter

From the P – wave velocity data, the elastic or Young's modulus of a test material can be obtained. In this testing program, 3 pulses per 6 seconds was used for testing EPS geofoam. The P – Distance was inputted and the P – Velocity was obtained from the experiment. A direct transmission method was selected as recommended by the instrument specifications. A high voltage and the maximum amplifier gain of 500 were used for the pulse wave. Even though the density option in the V – Meter was not used in this experiment, the least available option for density of 800 Kg/m^3 (50 lb/ft^3) was entered. The transducers were calibrated at the start of experiments of each testing day or after a change in coupling agent. Calibration of transducers involved holding both transducers in contact with the coupling agent in between and running the calibration function in the setup menu of the V - Meter.

Figure 3.7 Calibration of transducers

(a) (b)

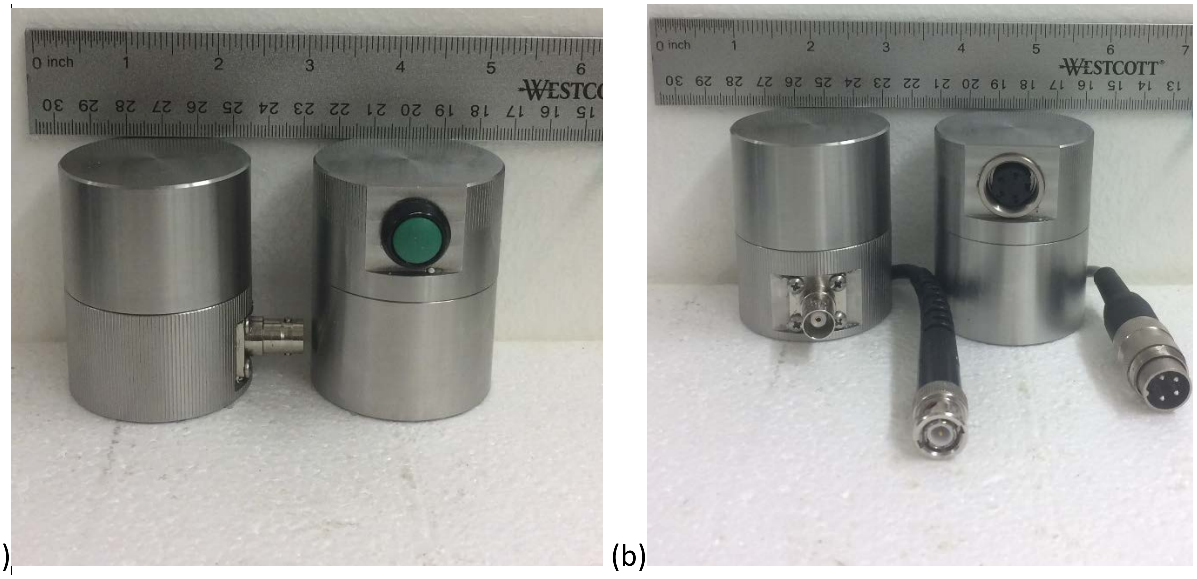


Figure 3.8 Triggering and receiving transducers (a) side view of transducers (b) connection ports of transducers

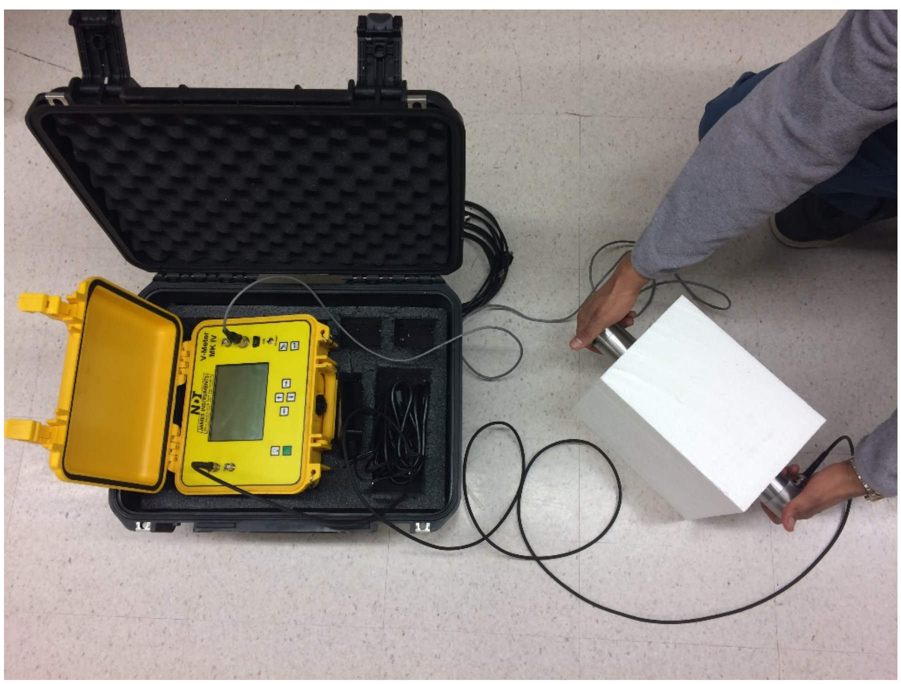


Figure 3.9 NDT on a small sample in the laboratory

The standard transducers supplied with the V – Meter generate a 54 kHz frequency wave. Higher frequency transducers are suitable for test material dimensions of up to 0.3 m (1 ft.) without using pre amplifiers. The 54 kHz transducers were able to test materials of length up to 5 m (16 ft.). Researchers have found that waves of different frequency propagate in different paths and result in different wave velocities (Shim, Guo, & Lan, 2008). This has bolstered the use of only one transducer frequency to provide a consistent analysis across the different densities of EPS block tested in this experiment.

3.5 Lab tests and preliminary results

Trial tests were performed on EPS samples obtained from Plant 1. Exhumed samples from prior projects were also tested. These EPS samples were of different sizes and densities. The collected P – wave velocities showed significant differences between different densities and good consistency on blocks of the same density. The EPS geofoam samples used for testing were of nominal densities that range from 16 to 40 Kg/m^3 (1 to 2.5 lb/ft^3). A range of data was obtained. The minima, maxima and average P wave velocities obtained are shown in Table 3-1 below.

Table 3-1 P wave velocity values obtained from EPS samples tested in the laboratory

Density, Kg/m³ (lb/ft³)	# of Velocity Readings	Sample Size, (cm³)	P – Wave Velocity, m/sec (ft/sec)			
			Minimum	Maximum	Average	Range
16 (1.00)	7	10 X 16 X 23	815 (2668)	935 (3061)	875 (2870)	120 (393)
	7	12 X 15 X 28				
	7	61 X 61 X 61				
	7	61 X 122 X 122				
20 (1.25)	10	15 X 15 X 30	700 (2299)	950 (3118)	830 (2721)	250 (819)
	10	15 X 23 X 30				
24 (1.50)	4	10 X 23 X 30	905 (2974)	935 (3064)	915 (3005)	30 (90)
	4	23 X 23 X 30				
32 (2.00)	4	10 X 18 X 30	945 (3095)	965 (3165)	955 (3126)	20 (70)
	4	25 X 25 X 25				
40 (2.50)	4	23 X 23 X 23	995 (3261)	995 (3265)	995 (3263)	0 (4)

Due to the limited availability of EPS samples in the lab, additional readings could not be taken. The average velocities indicate increases in velocity with density. The velocity range for the 16 and 20 Kg/m^3 (1 and 1.25 lb/ft^3) data are much wider possibly due to the presence of regrind. Information pertaining to the EPS samples' properties such as bead type, regrind content, mold date and molder, and expander types were not known for the lab tests. Field tests at EPS manufacturing plants was necessary to get more consistent results. More sample information was available for tests performed at the manufacturing plant.

Additional tests were conducted in the lab on samples containing different percentages of regrind. The tests were conducted on a 16 Kg/m^3 (1 lb/ft^3) nominal density EPS samples that are of virgin material only and containing 30%, 50%, and 100% regrind. The results obtained are summarized in Table 3-2.

Table 3-2 Average P wave velocities that were with 90% confidence level for virgin samples and samples with varying percentage of regrind

Block Type	**Mass (Kg)**	**Sample Size (cm^3)**	**Density Kg/m^3 (lb/ft^3)**	**No. of Velocity Readings taken**	**Average Velocity, m/sec (ft/sec)**
Virgin	0.10	16.5 X 20 X 20	15.2 (0.95)	20	770 (2520)
100% Regrind	0.05	10 X 10 X 30	16.7 (1.04)	20	235 (773)
50% Regrind	0.07	10 X 18 X 30	12.9 (0.81)	20	750 (2451)
30% Regrind	0.07	12 X 17 X 24	14.3 (0.89)	20	805 (2643)

As shown in Table 3-2, as the regrind percentage increases, the P wave velocity decreases for the same density EPS sample. However, the P wave velocity for the virgin sample is lower than the sample containing 30% regrind. Here again, the size of the sample tested, the number of velocity readings taken, and the confidence level to which these velocity readings are produced restrict the conclusions that can be reached.

Moreover, the P wave velocity obtained for the 16 Kg/m^3 (1 lb/ft^3) EPS virgin sample from Table 3-1 was higher than the one that was reported in Table 3-2. Visual description of the EPS samples shows a significant difference in bead composition between the two 16 Kg/m^3 (1 lb/ft^3) virgin samples. The sample size also may have contributed to the velocity variations between the EPS samples. This phenomena is investigated further by doing additional tests and with availability of more information about the samples.

4 Field Test Program

The encouraging results obtained in the laboratory experiments led to the decision to pursue field tests at four EPS geofoam manufacturing plants in in close proximity to Syracuse, NY. These plants are located in States of New York and Pennsylvania. Testing was performed on a total of 52 EPS geofoam blocks of different densities and regrind content. A total of 1016 velocity readings were made on full and half sized blocks at the manufacturing plants. A second round of tests were conducted on 7 blocks to compare velocities with an amplified P wave signal and an additional 2008 readings were made on EPS blocks.

One directional signal was checked on all three sides of the geofoam blocks. Signal was not obtained in the 2.5 and 5 m length for half sized and full sized EPS blocks respectively. Hence, testing was performed in the 0.6 or 1 m thickness blocks and standard width of 1.2 m. Signals were checked at 0.6 m spacing for testing on half sized blocks as shown in Figure 4.1a. In addition, high density EPS geofoam blocks that were stored vertically could not easily be rotated. Hence, testing was done 0.6 m apart on the bottom half of these high density blocks as shown in Figure 4.1b. However, EPS blocks of 16 and 20 Kg/m^3 (1 and 1.25 lb/ft^3) density were rotated and tested horizontally at 1.2 m spacing as shown in Figure 4.1c.

The plants have SUNGHOON, MOLDEX WISER, or HIRSCH make batch expanders and a conventional MOLDEX or a vacuum HIRSCH make block molder. Only one plant has a vertical mold whereas all other plants have horizontal molds. The temperature of the steam inside the mold is about 100^0C while the pressure ranges from at least 0.5 bars (BASF, 1998) to a maximum of 1.05 bars (BASF, 1994).

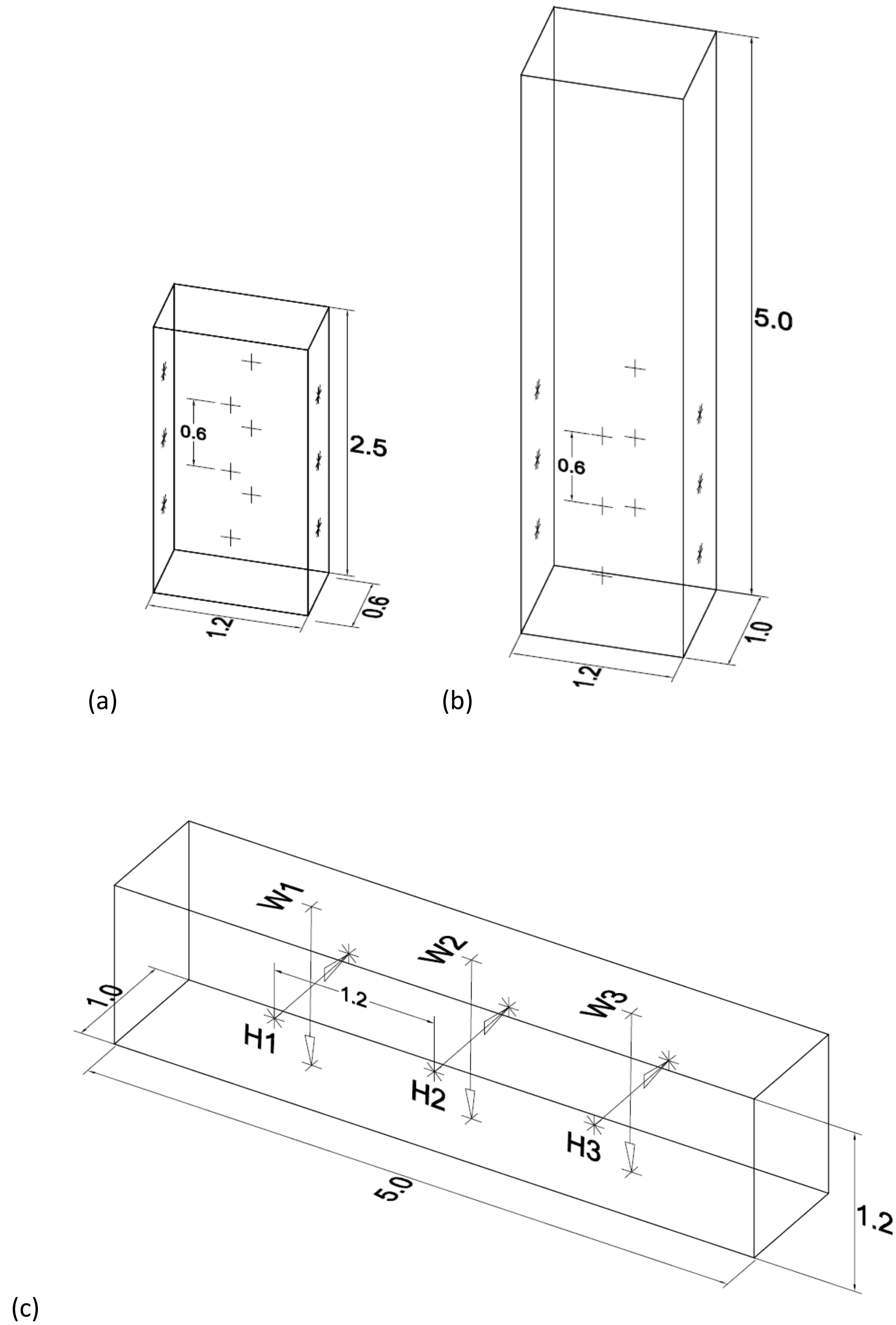


Figure 4.1 Testing locations and arrangement of EPS geofoam blocks (all dimensions are in m) H and W represent locations of tests along the thickness and width of the block respectively.

4.1 Plant 1

The field testing was performed at Plant 1 on the 28th of October 2016. The company produces EPS blocks of 16, 20, 24, and 32 Kg/m^3 (1, 1.25, 1.5, and 2 lb/ft^3) nominal densities. The 20 Kg/m^3 (1.25 lb/ft^3) EPS block is produced upon request by clients. In addition, it produces the 16 Kg/m^3 (1 lb/ft^3) EPS block with a 10% regrind or recycled content.

Figure 4.2 Bead expander

Blocks produced at Plant 1 have 0.6 X 1.2 X 5 m nominal dimensions. Tests were performed on a total of eight EPS geofoam blocks. The tested blocks were half sized blocks i.e. they had nominal dimensions of 0.6 X 1.2 X 2.5 m. The density, mold date, and type of bead used for the specific EPS geofoam block are shown in Figure 4.4a. All side dimensions and the mass of each individual EPS block was measured and recorded before moving on with the NDT. The EPS geofoam blocks tested are shown in Table 4-1.

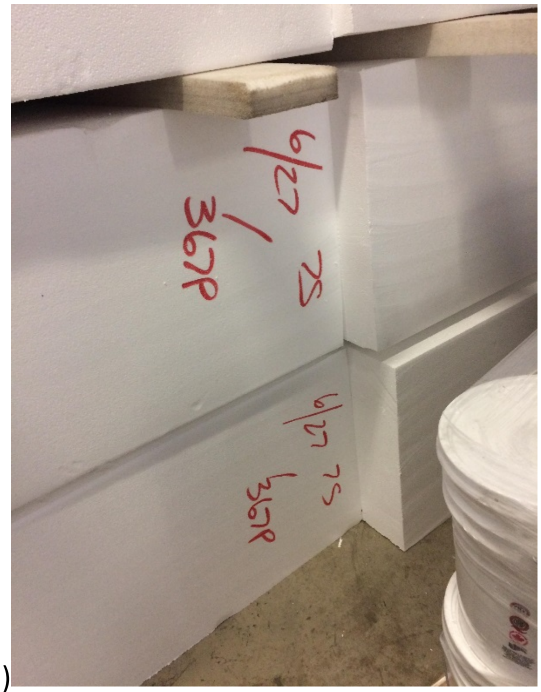
Table 4-1 EPS geofoam blocks tested at Plant 1 on Oct 28, 2016

Block No	Block ID	Volume (m^3)	Mass (Kg)	Density (Kg/m^3)	Mold Date	Regrind Content, %	Bead Type	Number of Velocity Readings
1	4121	2	26.3	13.2	10/26/2016	10	M464D	0
2	4121	2	26.3	13.2	-	10	M464D	0
3	5256	2	29.5	14.8	10/18/2016	0	5454	13
4	5256	2	30.0	15.0	10/18/2016	0	5454	24
5	4057	2	44.0	22.0	-	0	M464D	48
6	4051	2	45.0	22.5	10/03/2016	0	M464D	48
7	4051	2	59.4	29.7	10/25/2016	0	M464D	41
8	3067	2	63.1	32.0	10/24/2016	0	3454	35

Figure 4.3 The molding equipment

On block numbers 7 and 8, signal was not obtained from point W2 in the 1.2 m width of the block. Signals could not be obtained from both blocks with regrind content. Signals were also not obtained on the 1.2 m width for the blocks 3 and 4.The EPS geofoam blocks were placed on rollers for easy transportation to and from the storage. Hence, the effect of placing the EPS geofoam block on rollers were compared by testing the same blocks again on the ground.

(a)



(b)

Figure 4.4 (a) Labelled EPS blocks (b) EPS test block

Figure 4.5 EPS blocks in storage

Table 4-2 Second round testing of EPS blocks at Plant 1 on June 28, 2017

Block No	**Block ID**	**Volume (m^3)**	**Nominal Density (Kg/m^3)**	**Mold Date**	**Regrind Content, %**	**Bead Type**	**Number of Velocity Readings**		
							No Amp	**X4 Mag**	**X7 Mag**
1	167W	2	16	6/26/2017	10	BF395	0	63	59
2	167W	2	16	6/26/2017	10	BF395	0	25	52
3	367P	2	16	6/21/2017	0	BF395	62	125	128
4	4071	2	20	6/13/2017	0	M444D	126	125	125
5	5033	2	24	5/10/2017	0	5454	126	125	125
6	7784	2	32	6/15/2017	0	M77BLV	125	124	123
7	5990S	2	48	4/25/2017	0	S5454	124	122	124

A signal amplifier was purchased after the completion of the field testing program and an additional set of tests were conducted only at Plant 1 on June 28, 2017. One EPS block was tested for 16, 20, 24, 32, and 48 Kg/m^3 (1, 1.25, 1.5, 2, and 3 lb/ft^3) nominal densities. Two EPS blocks of 16 Kg/m^3 (1 lb/ft^3) of nominal densities that contained 10% regrind were also tested. The mass for the EPS blocks in Table 4-2 were not collected because the weighing scale was not in a reachable location from the testing site. However, these blocks are assumed to meet the criteria for 90% nominal density. The EPS blocks were made from resin beads supplied by Styropek, Nova Chemicals, and Flint Hills Resources (shown as BF, M, and 54 type in Table 4-2). Signals were not obtained in the blocks containing regrind and on the 1.2 m width of the 16

Kg/m^3 (1 lb/ft^3) nominal density without using the amplifier. With the amplifier, signals were obtained on certain locations of the regrind block and on all locations of the 1.2 m width for the 16 Kg/m^3 (1 lb/ft^3) nominal density block without regrind.

4.2 Plant 2

The field testing at Plant 2 was performed on the 17th of November 2016. Currently, Plant 2 provides EPS geofoams for lightweight roadways, bridge abutments, landscaping and green roofs. The plant produces EPS blocks that have nominal dimensions of 1 X 1.2 X 5 m.

Figure 4.6 Vertical mold

Figure 4.7 Measuring dimensions of EPS geofoam blocks

Plant 2 produces EPS geofoam blocks of different densities ranging from 16 to 80 Kg/m^3 (1 to 5 lb/ft^3). EPS geofoam blocks with 30% regrind content are also produced for different densities. The sources of the regrind material can be from external recycling or wastages from cuttings in house. The tested EPS blocks are shown in Table 4-3. The M type resin beads used by Plant 2 were supplied by Nova Chemicals.

Table 4-3 EPS geofoam blocks tested at Plant 2 on Nov 17, 2016

Block No	Block lot	Volume (m^3)	Mass (Kg)	Density (Kg/m^3)	Mold Date	Regrind Content, %	Bead Type	Number of Velocity Readings
1	173	6	82.0	13.7	11/15/2016	0	33MBHD	0
2	331	6	82.0	13.7	10/21/2016	0	33MBHD	0
3	251	6	104.0	17.3	09/22/2016	30	M77CG	0
4	289	6	113.4	18.9	11/10/2016	0	M77BG	18
5	284	6	113.4	18.9	11/10/2016	0	M77BG	13
6	370	6	122.5	20.4	11/10/2016	0	M77BG	17
7	28	6	122.5	20.4	10/24/2016	0	M77BG	15
8	189	6	172.4	28.7	11/09/2016	0	M77CG	19
9	180	6	172.4	28.7	11/09/2016	0	M77CG	35
10	119	6	181.4	30.2	11/09/2016	30	M77CG	15
11	11	6	218.0	36.3	09/20/2016	0	M77CG	32
12	24	6	220.0	36.7	06/13/2016	0	M77CG	22
13	24	6	272.2	45.4	11/10/2016	0	M77CG	27
14	309	6	272.2	45.4	10/07/2016	0	M77CG	32
15	307	6	356.1	59.4	10/07/2016	0	-	28
16	304	6	499.0	83.2	10/07/2016	0	-	20

Signals were not obtained through block numbers 1, 2, and 3. For blocks 5, 6, and 7, signal was only obtained through the 1 m thickness of the blocks. In addition, only 2 points (H2 and H3) on the 1 m thickness gave signals for block number 4. From the visual inspection of the blocks, block number 8 was a low quality EPS geofoam block.

4.3 Plant 3

Plant 3 supplies EPS geofoam blocks for bridge approach fills and roofing projects. Tests on EPS blocks were performed on the 7th of December 2016. The plant produces EPS blocks of 1 X 1.2 X 5 m nominal dimensions. However, the tests were performed on half sized blocks of 1 X 1.2 X 2.5 m blocks. Plant 3 produces EPS blocks from 16 to 48 Kg/m^3 (1 to 3 lb/ft^3) nominal densities. EPS geofoam blocks with 15% regrind content for nominal densities ranging from 16 to 24 Kg/m^3 (1 to 1.5 lb/ft^3) are produced at the plant. The regrind materials used are wastages from blocks that are made at the plant. The resin beads used at this plant are supplied by NexKemia and Flint Hills Resources (Bead Types that start with M and S respectively in Table 4-4).

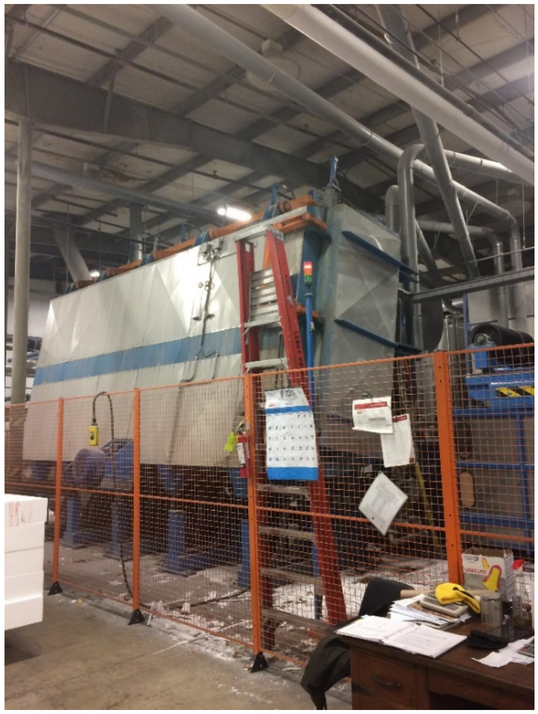


Figure 4.8 An EPS horizontal mold

Figure 4.9 A batch expander equipment

Table 4-4 EPS geofoam blocks tested at Plant 3 on Dec 7, 2016

Block No	Block lot	Volume (m^3)	Mass (Kg)	Density (Kg/m^3)	Mold Date	Regrind Content, %	Bead Type	Number of Velocity Readings
1	271133S-1	3	47.2	15.7	12/06/2016	0	S3454 / M464D	0
2	27133S-58	3	47.2	15.7	12/05/2016	0	S3454	0
3	6104111-11	3	53.0	18.0	10/28/2016	15	S3454	0
4	27078S-24	3	60.0	20.0	10/19/2016	0	M464D	15
5	27078S-24	3	60.0	20.0	10/19/2016	0	M464D	4
6	6104111-18 Geo	3	64.0	21.3	10/28/2016	0	M444D	14
7	23085-3	3	64.0	21.3	12/06/2016	15	M444D	0
8	6104111-18 Geo	3	64.4	21.5	10/28/2016	0	M444D	5
9	6114231-46	3	87.0	29.0	12/06/2016	0	S7454	24
10	6114231-45	3	88.0	29.3	12/06/2016	0	S7454	16
11	7548-6	3	113.4	38.0	11/22/2016	0	S7454	38
12	27094S-1	3	120.2	40.0	09/28/2016	0	S7454	31
13	27132S-19	3	138.0	46.0	12/05/2016	0	S7454	34
14	27132S-18	3	140.0	47.0	12/05/2016	0	S7454	36

Signal was not obtained through block numbers 1, 2, 3, and 7. For block numbers 5, 6, and 8, one point on the 1.2 m width (W1), all points on the 1 m thickness (H1, H2, and H3), and one point on the 1 m thickness (H2) gave signals respectively.

4.4 Plant 4

Plant 4 has supplied EPS geofoam transportation projects. The plant produces EPS blocks from 16 to 48 Kg/m^3 (1 to 3 lb/ft^3) nominal density. Tests at Plant 4 were conducted on the 12th of December 2016.

Figure 4.10 Using the V – meter on a full EPS block

EPS geofoam blocks produced by this plant have 1 X 1.2 X 5 m nominal dimensions.

Table 4-5 summarizes the information gathered from Plant 4.

Table 4-5 EPS geofoam blocks tested at Plant 4 on Dec 12, 2016

Block No	Block lot	Volume (m^3)	Mass (Kg)	Density (Kg/m^3)	Mold Date	Regrind Content, %	Bead Type	Number of Velocity Readings
1	E799	6	81.2	14.0	12/09/2016	35	MG64D	0
2	E864	6	87.1	14.5	12/12/2016	0	BF395	0
3	E194	6	87.0	14.5	11/02/2016	0	MB500E	0
4	E853	6	98.0	16.3	12/12/2016	15	BF395	0
5	D2329	6	110.2	18.4	11/28/2016	0	MB500E	15
6	E694	6	112.0	18.7	12/08/2016	0	MB500E	15
7	D1691	6	130.2	21.7	11/17/2016	0	S5454	26
8	C1696	6	130.0	21.7	10/19/2016	0	MB590L	15
9	D2274	6	176.0	29.3	11/28/2016	0	MB590L	37
10	E257	6	176.4	29.4	12/05/2016	0	MB590L	39
11	D1966	6	225.4	38.0	11/21/2016	0	I5354	32
12	D2296	6	261.3	44.0	11/28/2016	0	MB590L	19
13	E266	6	273.5	46.0	12/05/2016	0	MB590L	8
14	D2276	6	289.0	48.2	11/28/2016	0	MB590L	44

Block numbers 1, 2, 3, and 4 did not transmit detectable signals. Signals were obtained only in the 1 m thickness of the block for block numbers 5, 6, 8, and 12. The EPS geofoam blocks tested at Plant 4 were made with beads supplied by Styropek, Styro-Chem, NexKemia, and Flint Hills Resources (Bead Types that start with BF, MB, MG, and I/S respectively as shown in Table 4-5). The plant uses regrind from recycling and also from in plant cuttings.

5 Results

5.1 Nominal vs measured density

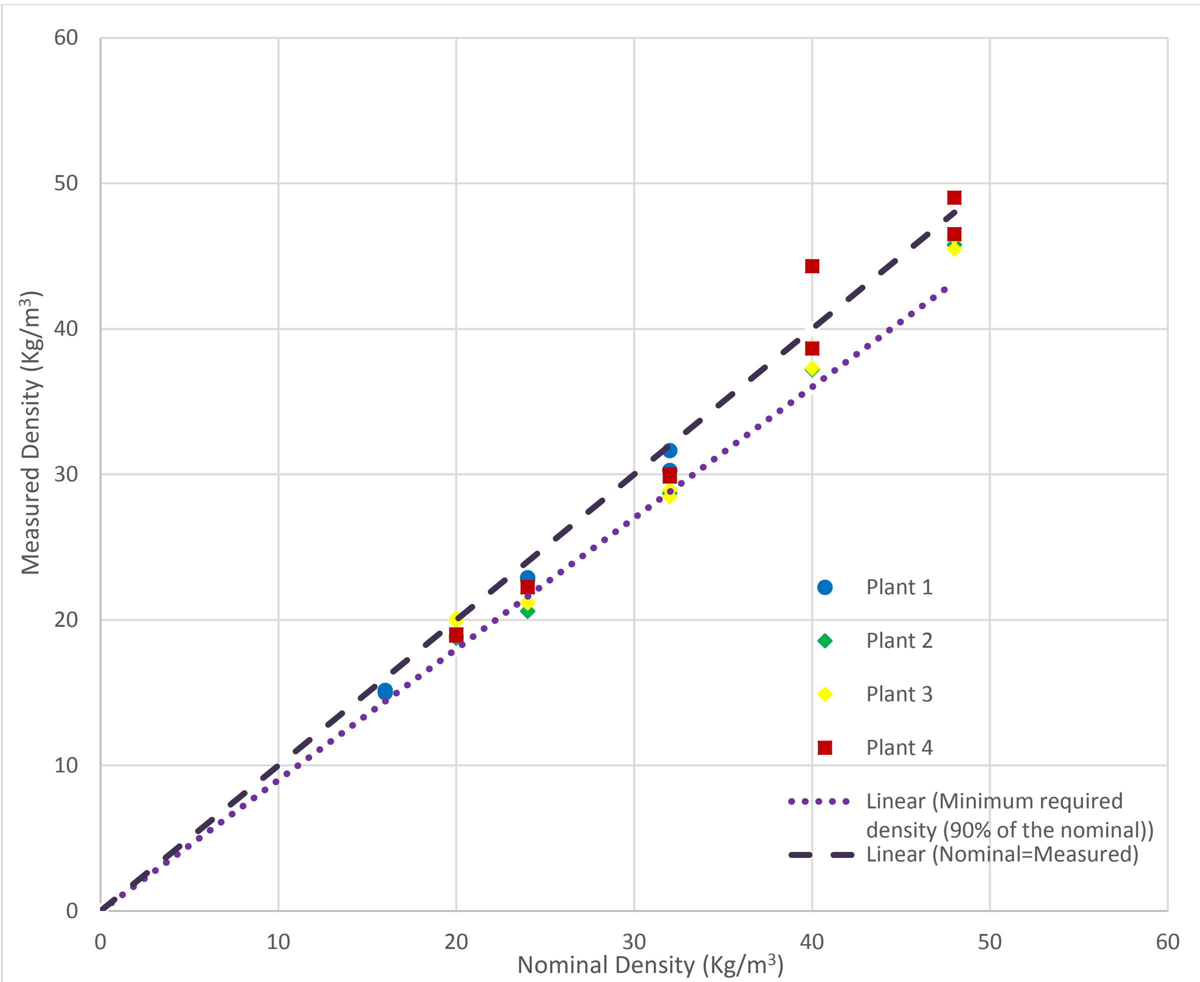


Figure 5.1 Nominal vs measured density (Kg/m^3)

From all plants testing data, the measured density values for each block tested were compared against the nominal density values and are shown in Figure 5.1 above. The nominal density values exist only in name and do not represent the actual density of the EPS blocks. All measured densities, except five, are at or above 90% of the nominal density usually specified as criteria for acceptance. Four blocks of 24 Kg/m^3 (1.5 lb/ft^3) and one block of 32 Kg/m^3 (2 lb/ft^3) nominal densities had a lower measured densities from the 90% minimum requirement. Two blocks were found to have higher measured densities than from their nominal densities. Seven EPS blocks, Table 4-2, that were tested with amplified signals were not re-weighed.

5.2 Density vs velocity relationships

5.2.1 Density vs velocity data for Plant 1

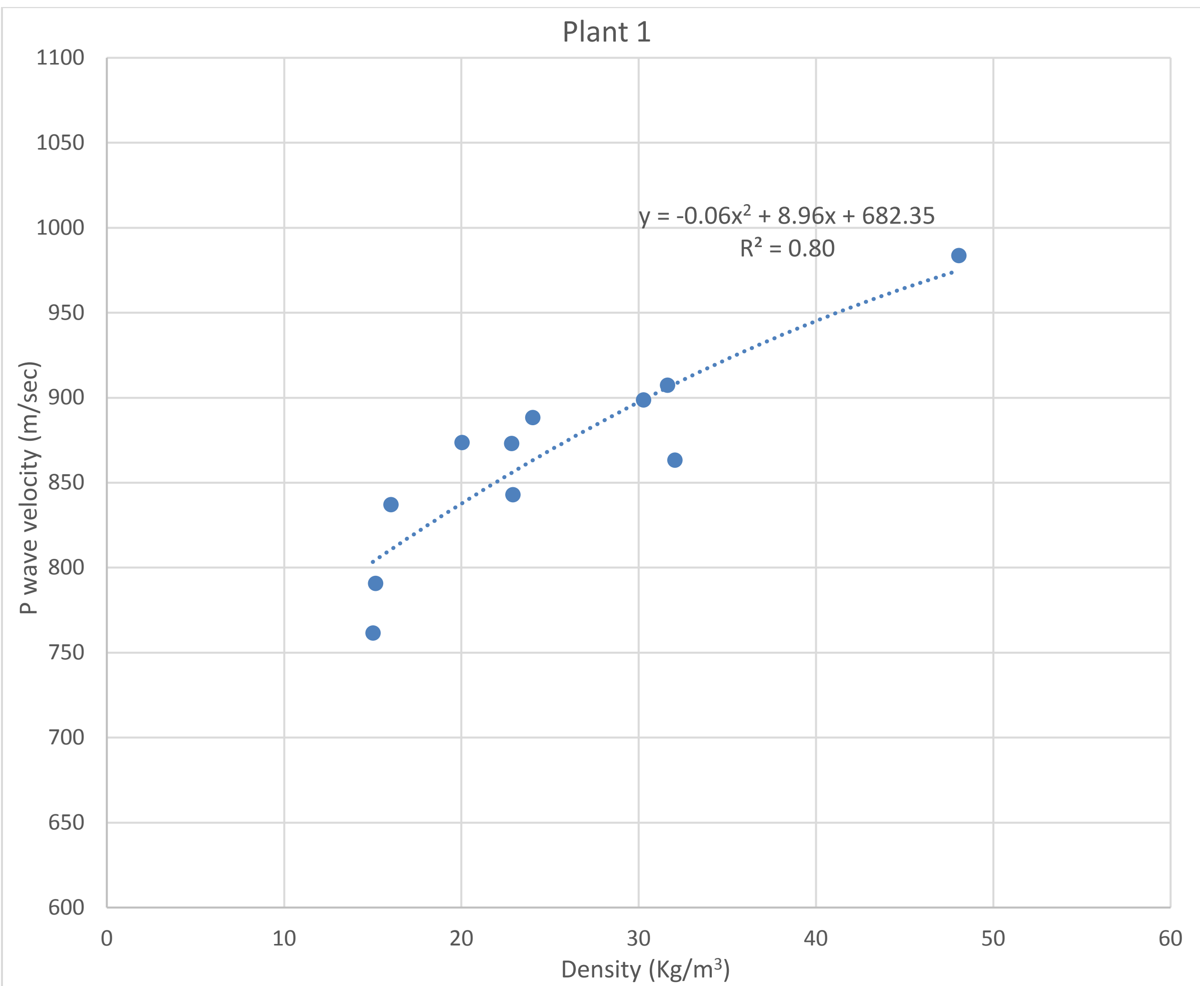


Figure 5.2 Measured density vs average velocity data for Plant 1

The data collected from Plant 1 shows a non – linear relationship of increasing velocity with density, Figure 5.2, with R – squared of 0.8. The non – linear relationship has a higher variability for the 16 Kg/m^3 (1 lb/ft^3) EPS block. The velocities shown in Figure 5.2 are obtained from tests using non amplified signals.

5.2.2 Density vs velocity data for Plant 2

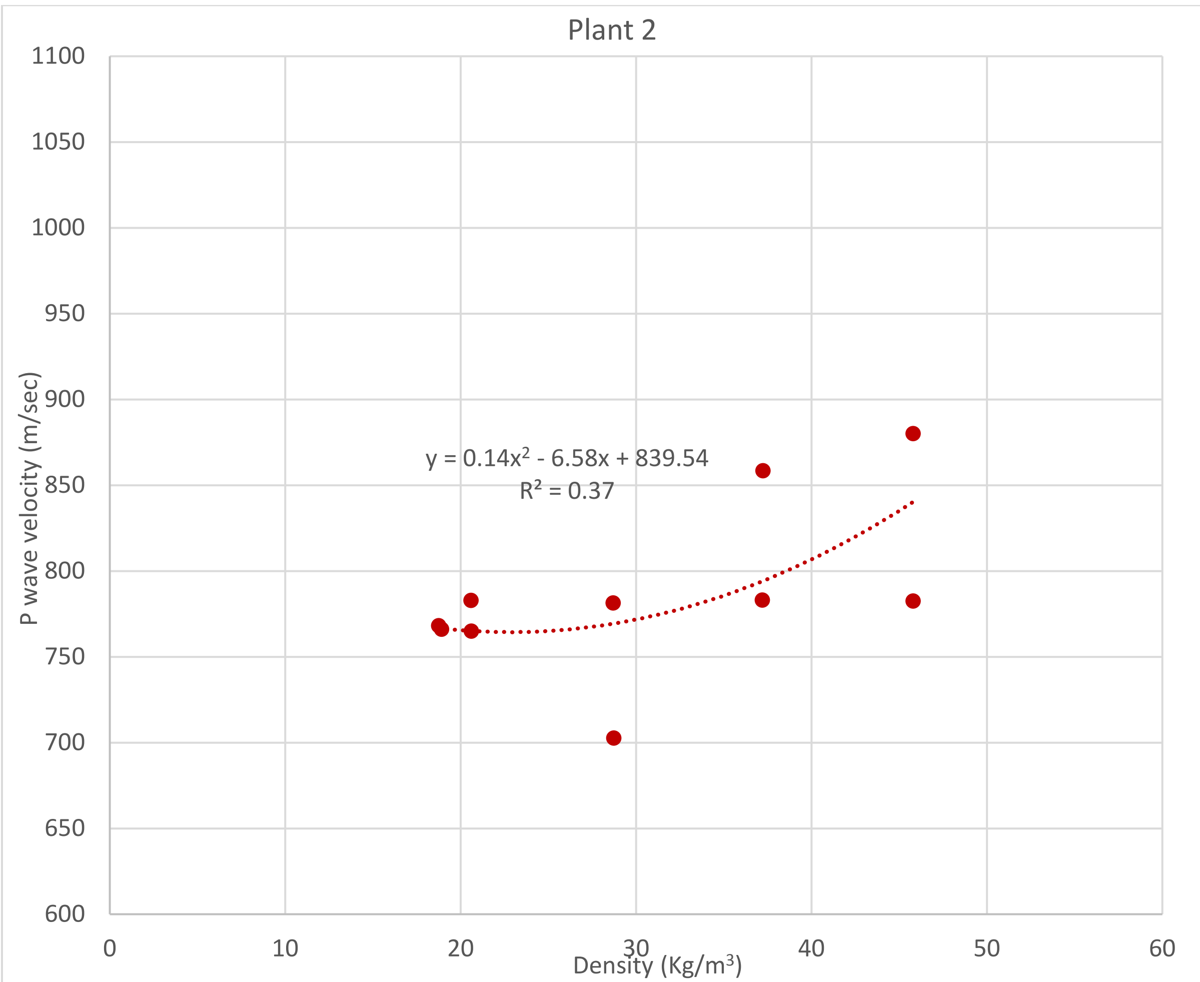


Figure 5.3 Measured density vs average velocity data for Plant 2

The Plant 2 velocity results are more scattered as indicated by the low R – squared value in Figure 5.3. There is more variability of velocity readings between different blocks but of the same 32, 40, and 48 Kg/m^3 (2, 2.5, and 3 lb/ft^3) nominal densities.

5.2.3 Density vs velocity data for Plant 3

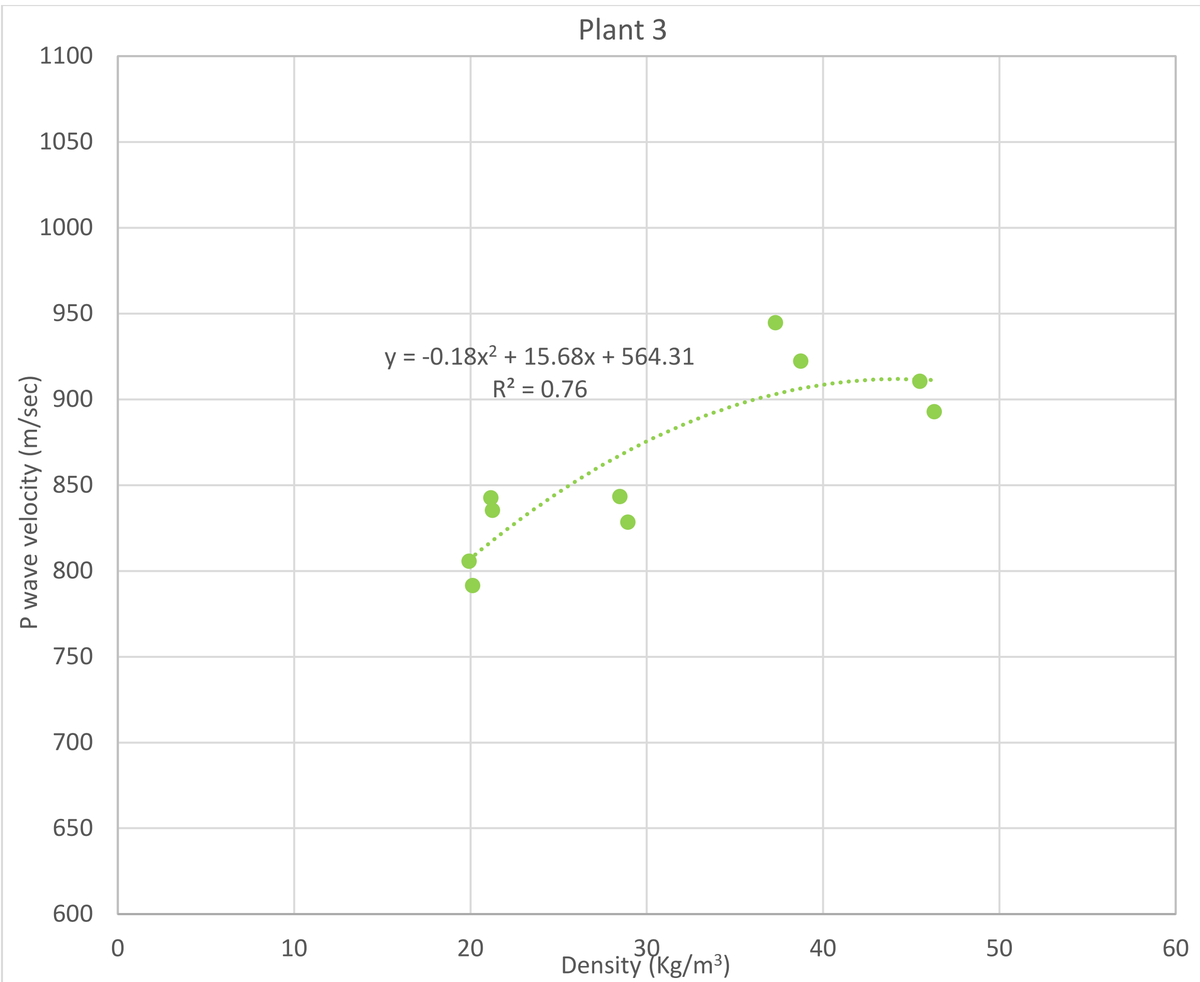


Figure 5.4 Measured density vs average velocity data for Plant 3

Figure 5.4 shows the density and velocity relationships for Plant 3. The R – squared value is less than Plant 1. There is a less variability in data than Plant 2 between same density blocks. Higher velocity readings are observed for the 40 Kg/m^3 (2.5 lb/ft^3) nominal density blocks.

5.2.4 Density vs velocity data for Plant 4

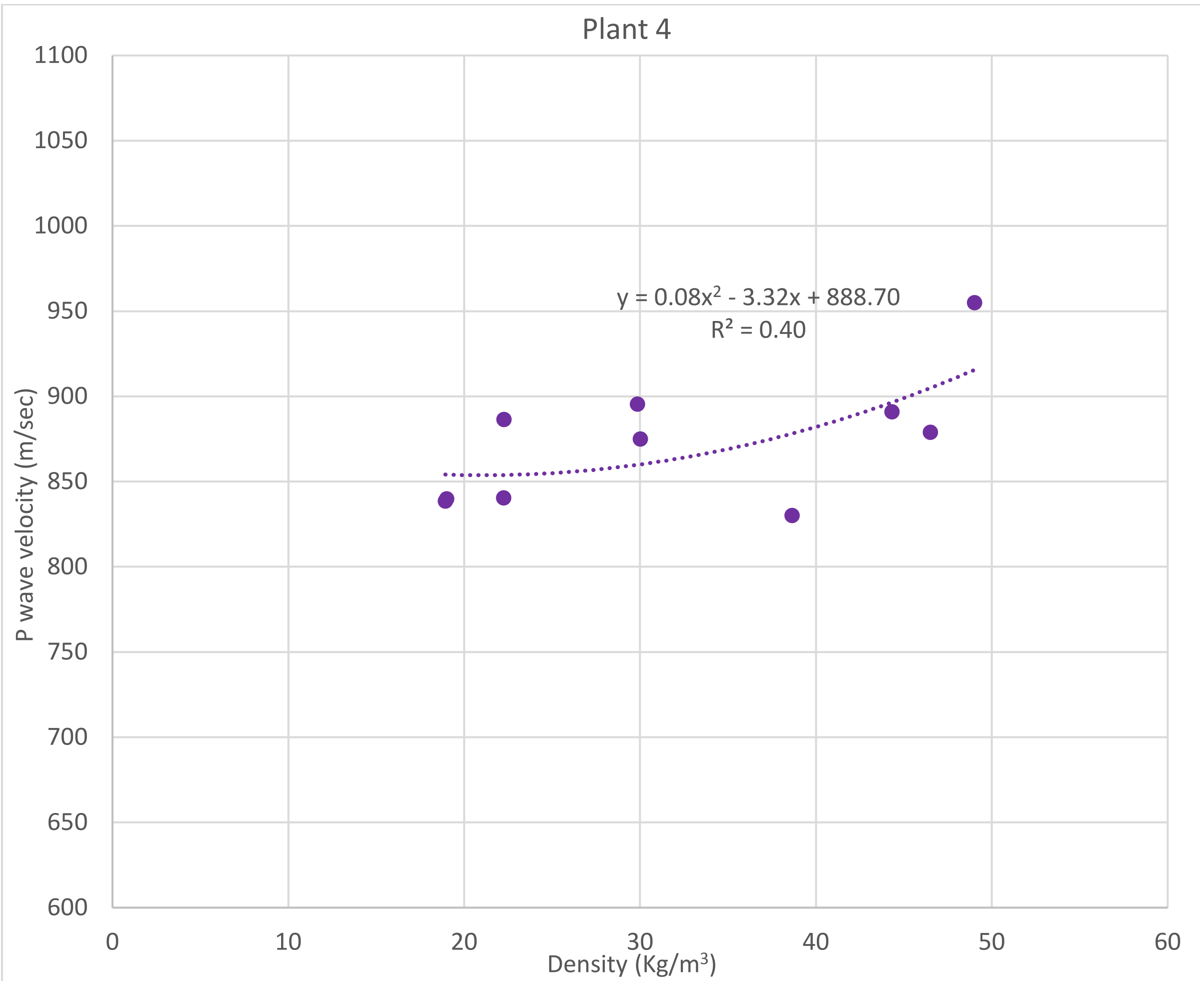


Figure 5.5 Measured density vs average velocity data for Plant 4

Figure 5.5 indicates significant variability in average velocity within the same density blocks of 24, 40, and 48 Kg/m^3 (1.5, 2.5, and 3 lb/ft^3) nominal densities. Unlike EPS block densities from the other plants, measured densities at Plant 4 were higher than the respective attributed nominal densities for 40 and 48 Kg/m^3 (2.5 and 3 lb/ft^3) density blocks.

5.3 Density vs velocity – comparison of all plants

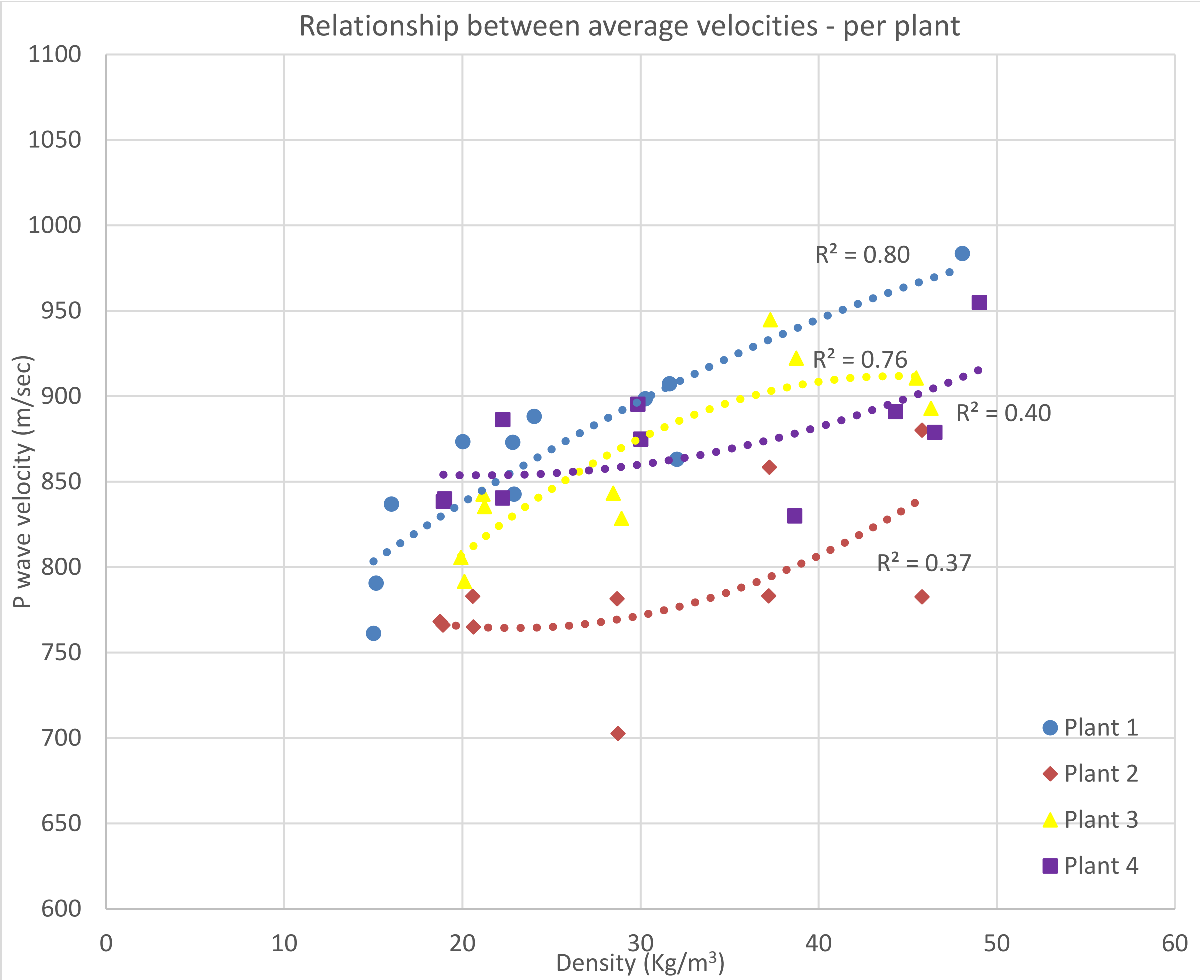


Figure 5.6 Measured density vs average velocity data per EPS plant

Figure 5.6 presents a summary of results for all four plants using non amplified signals. A polynomial relation of degree two provided the highest R – squared value for all plants. Velocities increased with density for all plants.

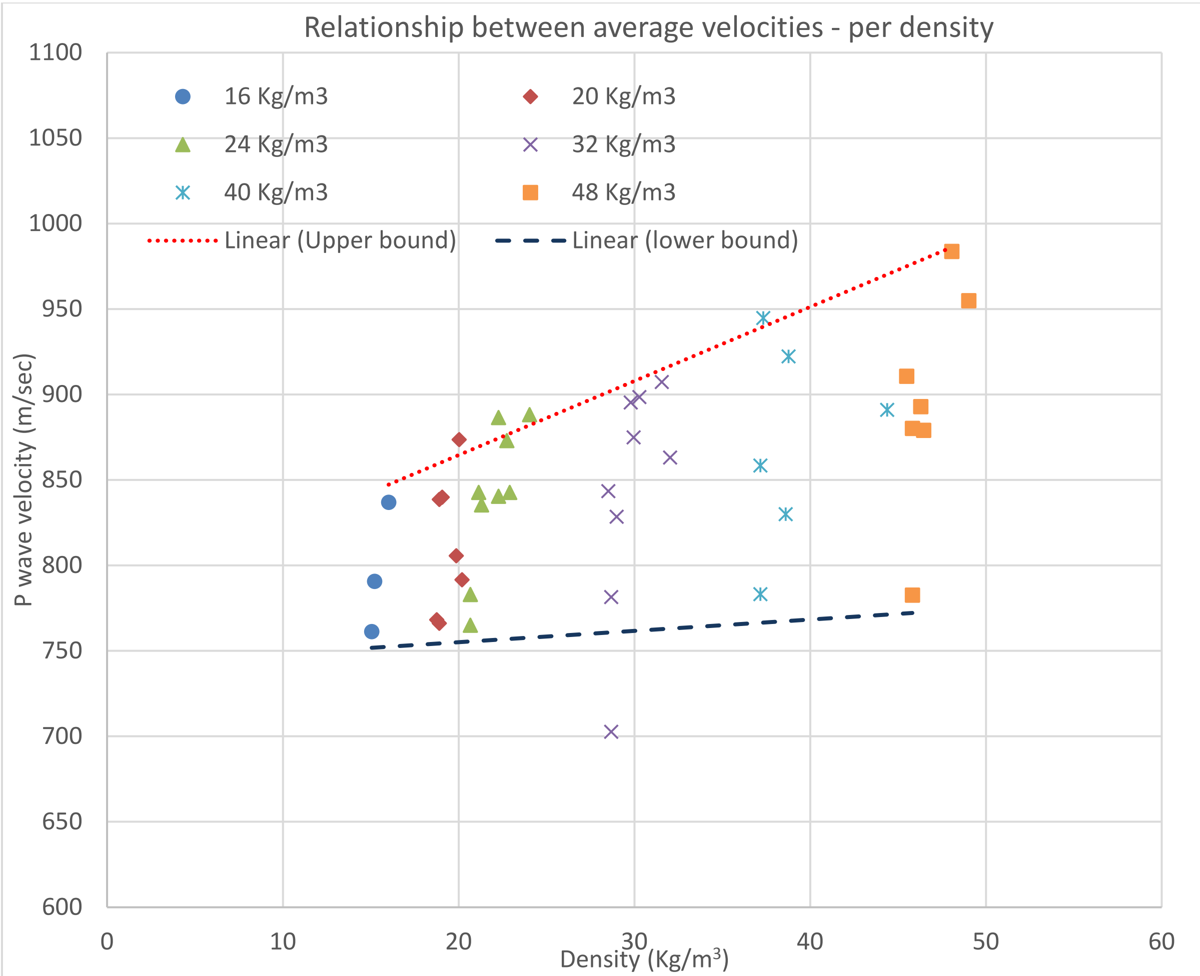


Figure 5.7 Measured density vs average velocity data per EPS density

The relationship for the collected data was further analyzed by grouping the data by EPS block type instead of per plant. Figure 5.7 shows the trend of increasing average velocity with density of EPS block. The average velocity values obtained from the higher density blocks (32, 40, and 48 Kg/m^3) have a larger range between the maximum and minimum values. Here again, the velocity readings recorded using non amplified signals are shown in Figure 5.7.

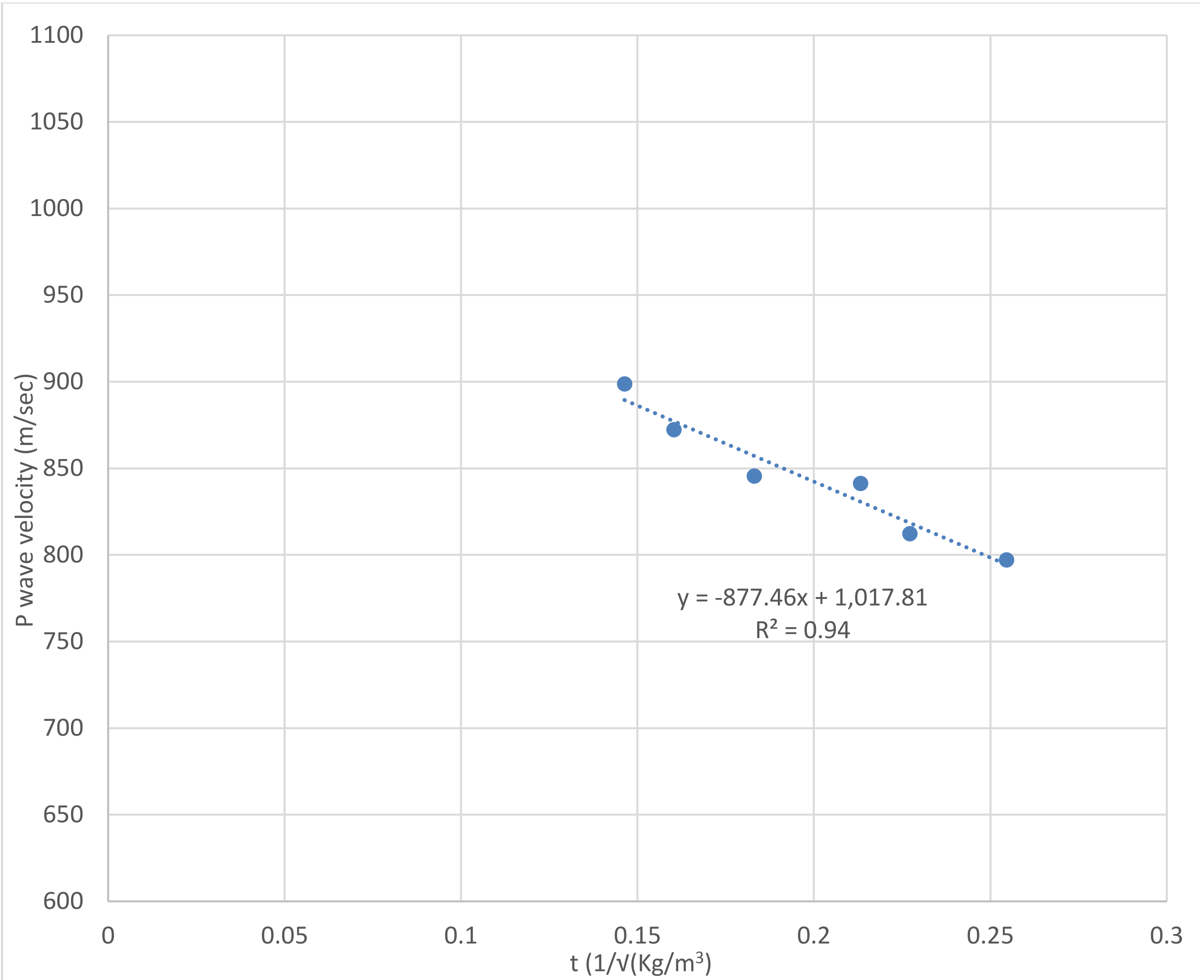


Figure 5.8 Defined variable “t” vs weighted average velocity squared

The weighted average velocity data shown in Figure 5.8 is a representation of the data shown in Figure 5.7. The weighted velocities are obtained by summing the product of the density of EPS blocks with their respective average velocities and then by dividing by the sum of the densities. The weighted velocity data is plotted against the inverse of the square root of density. A linear relation presents a high R – square value.

5.4 Computing Young's modulus for all densities

The Young's modulus of the EPS blocks were obtained using the following relation:

$$E = V^2 * \rho \qquad \text{Equation 1}$$

Where,

- E – the Young's Modulus of the block (psi)
- V – the average P wave velocity recorded by the V – Meter (ft/sec)
- ρ – mass density of the block in (lb/ft^3)

In Figure 5.6 and Figure 5.7, the velocities increased with density. This goes against the theoretical relationship in that velocity is inversely related to the square root of density. The reasoning behind the increase in velocity with density is that the modulus of the material does not stay constant with increase in density. Thus, the modulus compensates for the inverse relation between velocity and density.

Table 5-1 summarizes the average velocity values, sample size comparison for three different confidence levels, and Young's modulus obtained for all densities obtained from the different EPS geofoam manufacturing plants. The Young's modulus is calculated using the average velocities for each block. The average velocity and standard deviation of the block were calculated using the entire velocity data for each block.

The Young's moduli obtained for the blocks are much higher than those indicated by the ASTM 6817/D6817M – 15 for 1% strain. The Young's moduli for 20 and 24 Kg/m^3 (1.25 and 1.5 lb/ft^3) nominal density blocks are within reasonable range from each other in this testing program for all plants. However, the Young's modulus for both blocks of 32 Kg/m^3 (2 lb/ft^3) density from Plant 2 showed a significantly lower value than the values of similar densities from other plants. In addition, all blocks of 40 and 48 Kg/m^3 (2.5 and 3 lb/ft^3) nominal density from Plant 2 and two blocks of 40 and 48 Kg/m^3 (2.5 and 3 lb/ft^3) nominal density at Plant 4 exhibited inconsistencies in modulus values between blocks.

Table 5-1 Young's modulus calculated for EPS blocks tested

Plant	Density (lb/ft^3)	Density (Kg/m^3)	# of Velocity Readings, N	Velocity (ft/sec) Minimum	Maximum	Range	Mean	Standard Deviation	Modulus (psi)	Modulus (Mpa)	# of Velocity Readings for 95% CL, n5	# of Velocity Readings for 90% CL, n10	# of Velocity Readings for 80% CL, n20	Coefficient of Variation (%)
Plant 1	0.94	15.1	13	2474	2546	72	2496	23.95	1263	8.7	88	16	2	0.96
	0.95	15.2	24	2561	2619	58	2592	17.77	1377	9.5	49	9	1	0.69
	1.00	16.0	62	2581	2853	272	2744	83.69	1624	11.2	1076	190	29	3.05
	1.25	20.0	126	2744	2976	232	2864	77.79	2211	15.2	930	164	25	2.72
	1.42	22.7	48	2824	2899	75	2862	23.46	2509	17.3	85	15	2	0.82
	1.43	22.9	48	2642	2861	219	2763	75.46	2355	16.2	875	154	23	2.73
	1.50	24.0	126	2813	3013	200	2912	53.69	2743	18.9	443	78	12	1.84
	1.89	30.3	41	2860	3044	184	2946	44.47	3537	24.4	304	54	8	1.51
	1.97	31.6	35	2901	3075	174	2975	60.88	3760	25.9	570	100	15	2.05
	2.00	32.0	125	2708	2891	183	2830	50.20	3454	23.8	387	68	10	1.77
	3.00	48.1	124	3153	3351	198	3225	52.05	6729	46.4	416	73	11	1.61
Plant 2	1.17	18.7	18	2508	2531	23	2519	5.85	1601	11.0	5	1	0	0.23
	1.18	18.9	13	2479	2547	68	2512	17.85	1606	11.1	49	9	1	0.71
	1.29	20.7	17	2470	2533	63	2508	22.21	1751	12.1	76	13	2	0.89
	1.29	20.7	15	2559	2573	14	2567	4.60	1833	12.6	3	1	0	0.18
	1.79	28.7	19	2034	2440	406	2304	142.59	2049	14.1	3124	550	84	6.19
	1.79	28.7	35	2502	2615	113	2562	47.21	2535	17.5	343	60	9	1.84
	2.32	37.2	32	2325	3416	1091	2568	304.76	3300	22.7	14272	2513	382	11.87
	2.32	37.2	22	2710	2889	179	2815	64.24	3964	27.3	634	112	17	2.28
	2.86	45.8	27	2438	2716	278	2566	82.70	4061	28.0	1051	185	28	3.22
	2.86	45.8	32	2815	2941	126	2886	37.29	5136	35.4	214	38	6	1.29
Plant 3	1.24	19.9	4	2641	2642	1	2642	0.43	1866	12.9	0	0	0	0.02
	1.26	20.2	15	2518	2669	151	2595	46.31	1830	12.6	329	58	9	1.78
	1.32	21.1	14	2738	2802	64	2763	27.62	2173	15.0	117	21	3	1.00
	1.33	21.3	5	2720	2756	36	2739	12.77	2152	14.8	25	4	1	0.47
	1.78	28.5	24	2707	2813	106	2765	31.37	2935	20.2	151	27	4	1.13
	1.81	29.0	16	2689	2777	88	2716	30.81	2880	19.9	146	26	4	1.13
	2.33	37.3	38	2993	3195	202	3098	41.81	4821	33.2	269	47	7	1.35
	2.42	38.8	31	3005	3033	28	3024	5.31	4773	32.9	4	1	0	0.18
	2.84	45.5	34	2922	3023	101	2986	29.65	5460	37.6	135	24	4	0.99
	2.89	46.3	36	2780	3029	249	2928	75.72	5342	36.8	881	155	24	2.59
Plant 4	1.18	18.9	15	2729	2763	34	2749	10.15	1923	13.3	16	3	0	0.37
	1.19	19.1	15	2744	2772	28	2754	9.38	1947	13.4	14	2	0	0.34
	1.39	22.3	26	2883	2929	46	2906	13.80	2532	17.5	29	5	1	0.47
	1.39	22.3	15	2742	2775	33	2756	12.17	2277	15.7	23	4	1	0.44
	1.86	29.8	37	2901	2989	88	2936	30.52	3457	23.8	143	25	4	1.04
	1.87	30.0	39	2815	2928	113	2869	37.10	3319	22.9	212	37	6	1.29
	2.41	38.6	32	2628	2820	192	2721	70.34	3849	26.5	760	134	20	2.58
	2.77	44.4	19	2909	2937	28	2921	10.73	5098	35.2	18	3	0	0.37
	2.90	46.5	8	2780	2965	185	2882	53.36	5194	35.8	437	77	12	1.85
	3.06	49.0	44	3119	3152	33	3131	10.35	6469	44.6	16	3	0	0.33

5.5 Density vs velocity for 90% confidence level

The density and velocity relationships for each plant were compared using the velocity values for EPS blocks that are with 90% confidence level as shown in Figure 5.9. The underlined values under the 95%, 90%, and 80% confidence level columns in Table 5-1 indicate plants that meet the criteria of confidence.

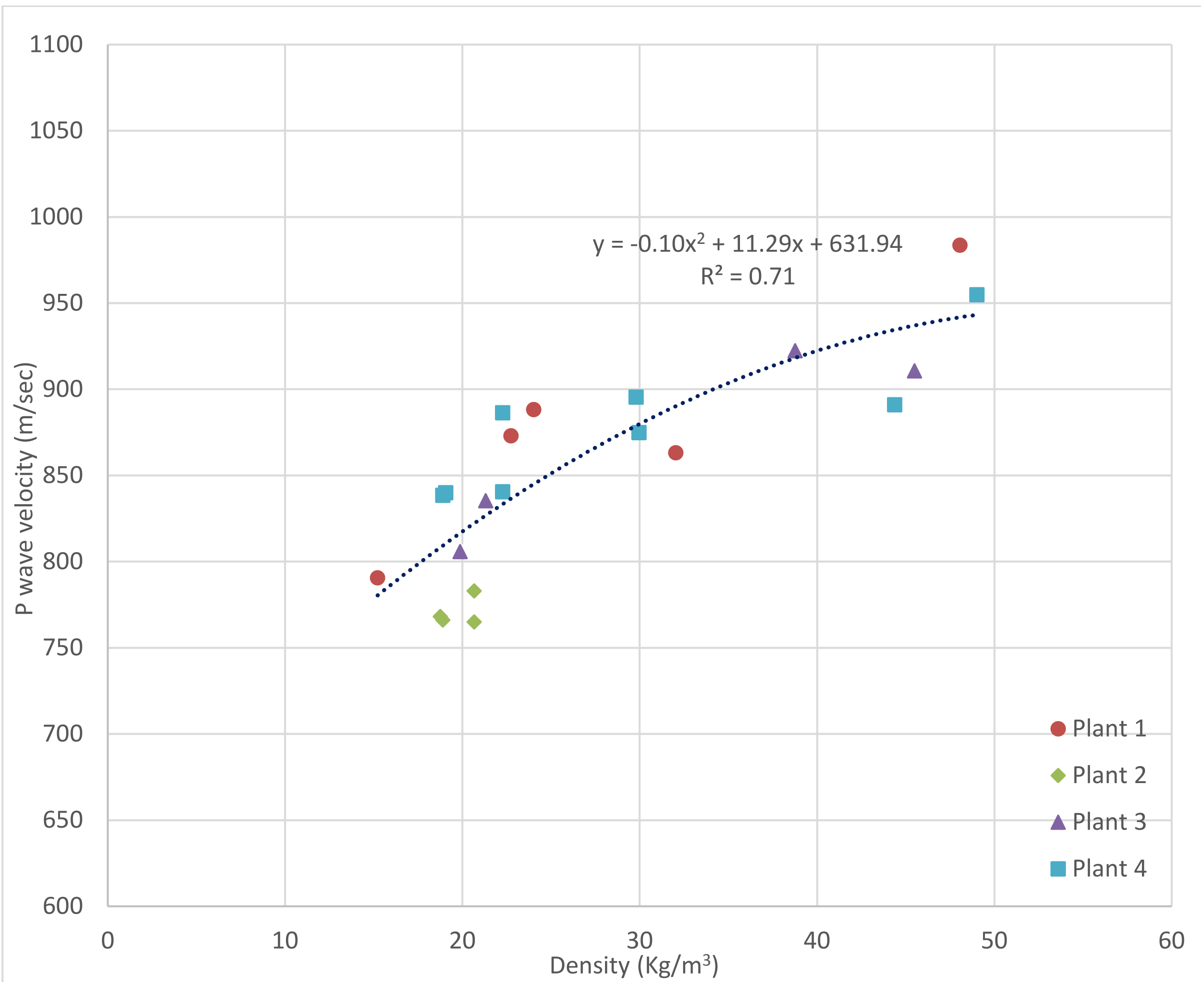


Figure 5.9 Measured density vs average velocity for 90% CL for plants

Figure 5.9 shows a high R – squared value for a polynomial relation of degree two for all plants data that are within 90% confidence level. Plant 4 had the most blocks that are within 90% confidence level.

5.6 Velocity comparison in amplified and non-amplified signals

The challenge to obtaining signals in this field test program was assumed to be due to a small wave amplitude of the P wave. To check this assumption an amplifier was purchased from James Instruments Inc. to test EPS blocks that previously did not transmit signals at Plant 1. For this second round testing, 10 pulses per 5 seconds was selected for the P wave option.

Table 5-2 Average velocity values for 90% CL of the amplified signal at Plant 1

Block	**Density (Kg/m^3)**	**Average Velocity, m/sec (# of velocity readings)**		
		Without Amplification	**X4 Amplification**	**X7 Amplification**
1	16 (w/ 10% regrind)	No Signal	767 (63)	768 (59)
2	16 (w/ 10% regrind)	No Signal	810 (25)	729 (52)
3	16	847 (42)	883 (125)	883 (128)
4	20	874 (126)	889 (125)	892 (125)
5	24	888 (126)	908 (125)	909 (125)
6	32	868 (104)	880 (124)	883 (123)
7	48	984 (124)	988 (122)	989 (124)

The data collected in the second round of tests at Plant 1 is shown above in Table 5-2. Tests were conducted at points H1, H2, H3, W1, W2, and W3 as shown in Figure 4.1. An average of 21 velocity readings were taken for each point. All blocks were tested with and without amplifying the P wave amplitude. An amplifier that is capable of amplifying the input signal 4 and 7 times was used in this experiment. The velocity readings shown in Table 5-2 using the amplifier are values that are about 5% higher than the readings taken without the amplifier.

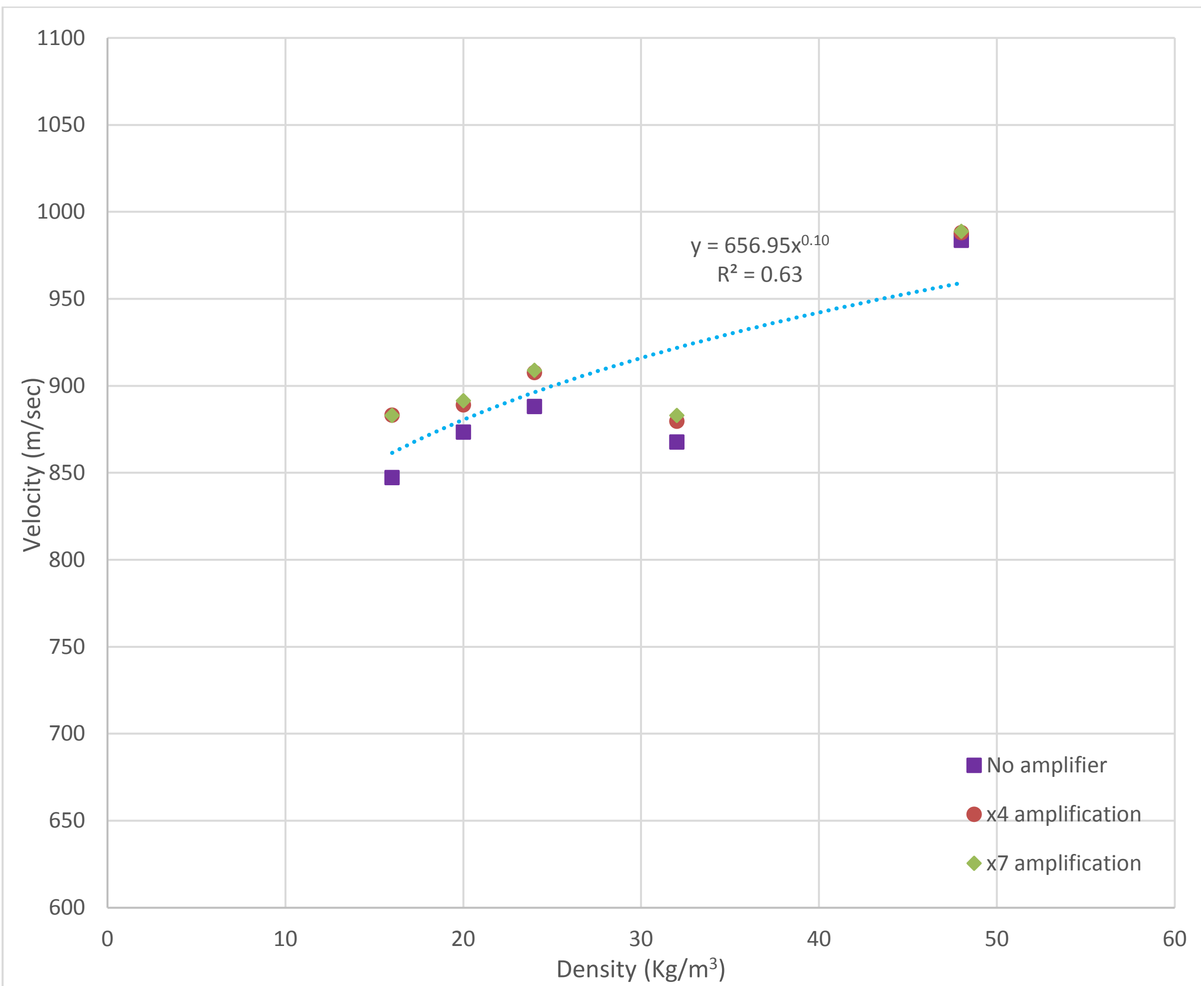


Figure 5.10 Average velocities for amplified and non-amplified signal that are within 90% CL for tests at Plant 1 vs EPS block density

Figure 5.10 shows the values for the virgin blocks presented in Table 5-2. The expected concave downward relation is observed in Figure 5.10 using a power relation. This change in best fit lines from a polynomial to power relation between Figure 5.9 and Figure 5.10 shows the complex relationship between velocity and density.

Table 5-3 presents the confidence levels for the tests performed at each point on the 0.6 m thickness and 1.2 m width for blocks tested shown in Table 5-2. The number of readings taken at each test location (H1, H2, H3, W1, W2, and W3) on EPS blocks were individually checked to satisfy 95 and 90% confidence levels. P wave signals were not obtained from points shown in italics and are in bold format. Points that are underlined failed to meet the criteria for confidence level while the remaining points meet the criteria.

Table 5-3 Confidence levels for second round tests at Plant 1

Block	Confidence Levels											
	95%						90%					
	No Amplification		X4 Amplification		X7 Amplification		No Amplification		X4 Amplification		X7 Amplification	
	25"	48"	25"	48"	25"	48"	25"	48"	25"	48"	25"	48"
Block 1	***H1***	***W1***	<u>H1</u>	W1	H1	W1	***H1***	***W1***	H1	W1	H1	W1
	H2	***W2***	***H2***	***W2***	***H2***	***W2***	***H2***	***W2***	***H2***	***W2***	***H2***	***W2***
	H3	***W3***	H3	***W3***	H3	***W3***	***H3***	***W3***	H3	***W3***	H3	***W3***
Block 2	***H1***	***W1***	<u>H1</u>	***W1***	H1	***W1***	***H1***	***W1***	H1	***W1***	H1	***W1***
	H2	***W2***	***H2***	W2	***H2***	W2	***H2***	***W2***	***H2***	W2	***H2***	W2
	H3	***W3***	***H3***	***W3***	H3	***W3***	***H3***	***W3***	***H3***	***W3***	H3	***W3***
Block 3	H1	***W1***	H1	W1	H1	W1	H1	***W1***	H1	W1	H1	W1
	<u>H2</u>	***W2***	H2	W2	H2	<u>W2</u>	<u>H2</u>	***W2***	H2	W2	H2	W2
	<u>H3</u>	***W3***	H3	W3	H3	W3	H3	***W3***	H3	W3	H3	W3
Block 4	H1	<u>W1</u>	H1	W1	H1	W1	H1	W1	H1	W1	H1	W1
	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2
	<u>H3</u>	W3	H3	<u>W3</u>	H3	<u>W3</u>	H3	W3	H3	W3	H3	W3
Block 5	H1	<u>W1</u>	H1	W1	H1	W1	H1	W1	H1	W1	H1	W1
	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2
	H3	<u>W3</u>	H3	W3	H3	W3	H3	W3	H3	W3	H3	W3
Block 6	H1	W1	H1	W1	H1	W1	H1	W1	H1	W1	H1	W1
	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2
	H3	<u>W3</u>	H3	<u>W3</u>	H3	W3	H3	<u>W3</u>	H3	W3	H3	W3
Block 7	H1	W1	H1	W1	H1	W1	H1	W1	H1	W1	H1	W1
	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2	H2	W2
	H3	W3	H3	W3	H3	W3	H3	W3	H3	W3	H3	W3

6 Discussion

6.1 Comparison of modulus with other findings

From the compressive resistance indicated in ASTM D6817/D6817M – 15, the Young's moduli of the different densities of EPS geofoam are obtained using Equation 1. These values are indicative of properties of 50 mm (2 inch) cube EPS geofoam samples.

Table 6-1 Young's modulus calculated from ASTM D6817/D6817M – 15

EPS Type	**Density, min kg/m^3 (lb/ft^3)**	**Compressive Resistance at 1% strain, min kPa (psi)**	**Young's Modulus, min MPa (psi)**
EPS 15	14.4 (0.90)	25 (3.6)	2.5 (360)
EPS 19	18.4 (1.15)	40 (5.8)	4.0 (580)
EPS 22	21.6 (1.35)	50 (7.3)	5.0 (730)
EPS 29	28.8 (1.80)	75 (10.9)	7.5 (1090)
EPS 39	38.4 (2.40)	103 (15.0)	10.3 (1500)
EPS 46	45.7 (2.85)	128 (18.6)	12.8 (1860)

The comparison between the Young's moduli obtained from the V – Meter testing and the ASTM D6817/D6817M – 15 values provided in Table 5-1 and Table 6-1, respectively, are shown in Figure 6.1. The Young's modulus values obtained from the V – Meter testing program far exceed the values from ASTM D6817/D6817M – 15. However, it can be seen that the data for the 32, 40, and 48 Kg/m³ (2, 2.5, and 3 lb/ft³) nominal densities contain more variations in their Young's modulus values.

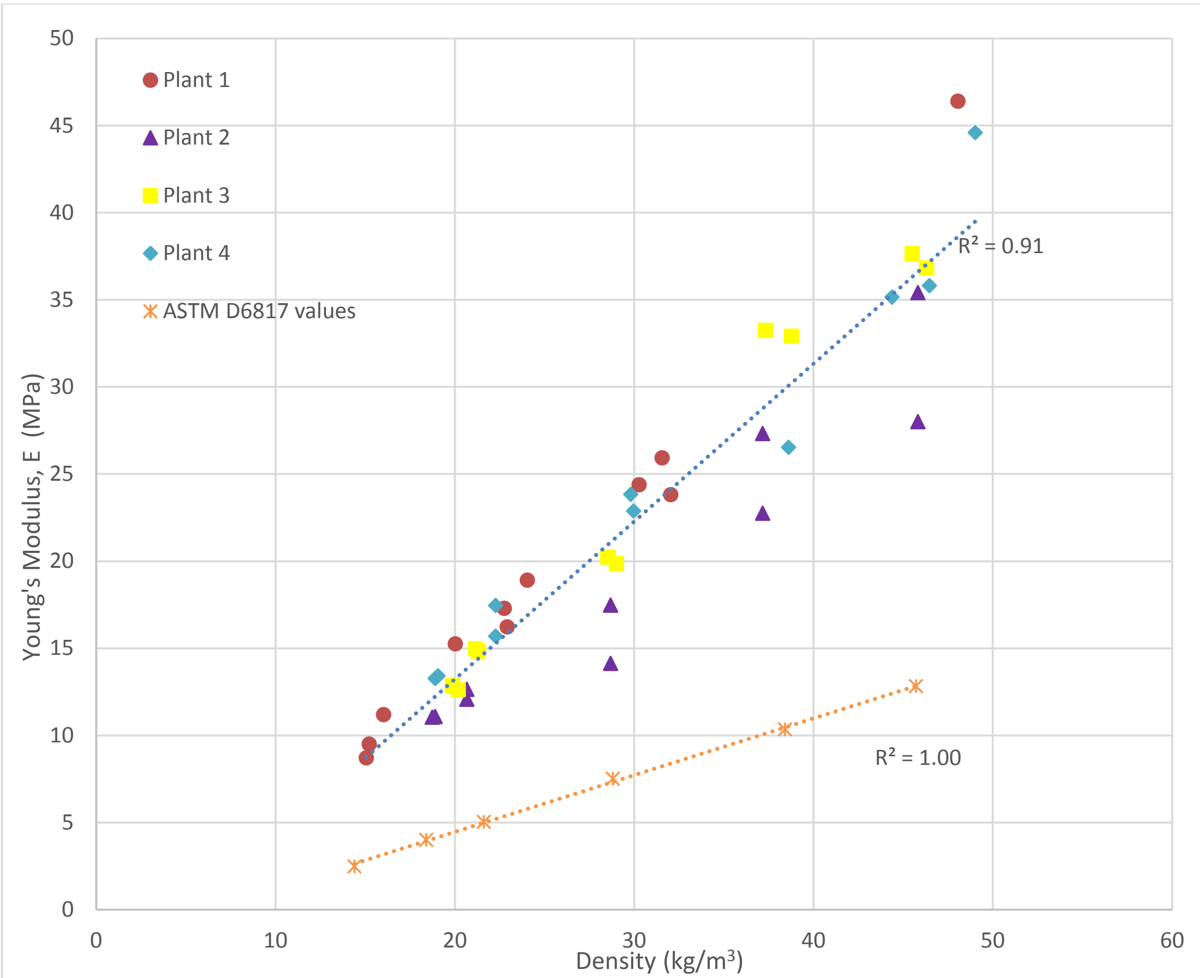


Figure 6.1 Young's modulus comparison between data from all plants and ASTM D6817/D6817M – 15

Average values of 17 MPa (2466 psi) and 26 MPa (3771 psi) were obtained from bender element testing for P waves of 350 – 500 Hz and 500 – 2000 Hz frequencies respectively on small EPS geofoam samples of 20 Kg/m³ (1.25 lb/ft³) density (Sivathayalan, Negussey, & Vaid, 2001). For the same density blocks, modulus values ranging from 11 MPa (1600 psi) to 16 MPa (2320 psi) were obtained from the V – Meter data. The modulus values predicted by both range of frequencies from the bender element testing present values that are higher than the moduli values obtained for the same density by the V – Meter testing from all plants.

Duskŏv (1997) tested cylindrical samples of 150 mm diameter and 300 mm height of EPS geofoam in uniaxial compression equipment at a strain rate of 7% per minute. Young's modulus values of 4.9 MPa and 7.4 MPa were obtained for EPS 15 and EPS 20 density samples. The relationship shown in Equation 2 was provided to determine the Young's modulus for EPS geofoam.

Two sets of cubic specimens measuring 50 mm and 400 mm and an additional specimen measuring 200 X 200 X 165 mm making a total of 162 specimens having a nominal density of 20 Kg/m^3 were tested at strain rates of 1, 2 and 10% per minute (Eriksson & Trank, 1991). From the compressive property determined, Young's moduli for EPS geofoam blocks were recommended to be estimated using Equation 3.

Elragi (2000) tested cubic specimens of dimension 50 mm and cylindrical specimens of 150 mm from an EPS 29 density block tested in unconfined compression at a strain rate of 10% per minute. Young's modulus values of 7.7 MPa and 9.3 MPa were obtained from the deformation of the cubic specimen and from an extensometer mounted at the middle third of the cylindrical specimens, respectively.

Simple bending tests were used to determine and compare the Young's modulus properties of EPS geofoam (Negussey & Anasthas, 2001). Tests were conducted on 75 mm and

100 mm wide samples and a relationship between the Young's modulus and density of EPS geofoam was developed. The relationship in Equation 4 was obtained from the bending test and the relationship in Equation 5 was provided for obtaining the Young's modulus for larger EPS geofoam samples from results obtained by testing cubic 50 mm samples (Negussey & Anasthas, 2001).

$$E_{EPS} = 0.1284 * \rho^{1.368} \qquad \text{Equation 2}$$

$$E_{EPS} = 0.01 * \rho^2 - 0.014 * \rho + 1.8 \qquad \text{Equation 3}$$

$$E_{EPS} = 0.82 * \rho - 4.9 \qquad \text{Equation 4}$$

$$E_{bending} \sim 2.3 * E_{50} \qquad \text{Equation 5}$$

Where,

- E_{EPS} – the Young's modulus (MPa)
- E_{50} – Young's modulus obtained from a 50 mm sample (MPa)
- ρ – density of the EPS geofoam (Kg/m^3)

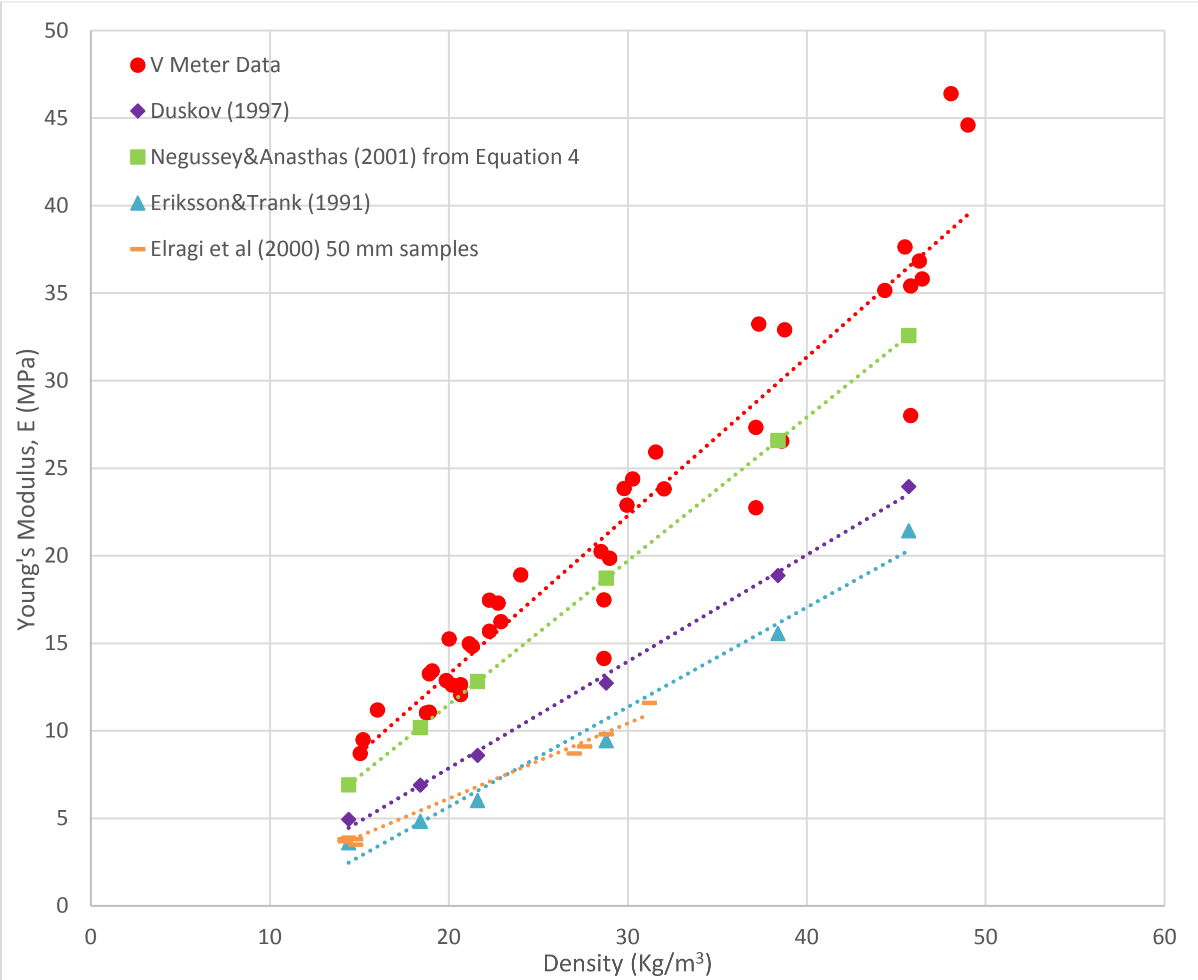


Figure 6.2 Young's modulus comparison with small specimen testing

Figure 6.2 shows the relations between density and modulus from small specimen testing. The relationship indicated in Equation 4 from the bending tests provides data that is close to the results obtained from the V – Meter testing program. The lower values obtained from the other relations clearly shows the sample size effect in EPS geofoam properties.

The Young's modulus values obtained from the V – Meter testing program were again compared against previously obtained values for large EPS geofoam samples. The moduli obtained from the V – Meter testing were compared with results obtained from the surface wave analysis of an EPS geofoam block with dimensions 0.96 X 1.22 X 7.32 m (Kafash, Arellano, Hosseini, & Pezeshk, 2013). The EPS block in this analysis is an EPS 22 geofoam having a density of 20.9 Kg/m^3 (1.3 lb/ft^3). An average shear modulus of 12.2 MPa (1770 psi) was obtained from the surface wave tests. The Young's modulus value for this block was then calculated using Equation 6 by assuming a total Poisson's ratio values from Elragi et al (2000).

$$E = 2 * G * (1 + \mu) \qquad \text{Equation 6}$$

Where,

- E – the Young's modulus
- G – the shear modulus
- μ – the Poisson's ratio

The calculated Young's modulus from the shear modulus value was found to be 26.8 MPa (3893 psi), 29.3 MPa (4247 psi), and 31.7 MPa (4601 psi) by using Poisson's ratio values of 0.1, 0.2, and 0.3 respectively. These values significantly exceed (approximately twice) the Young's modulus values obtained by the V – Meter testing. The Young's modulus values shown for this density in Table 5-1 provide conservative values when compared to this surface wave EPS Geofoam block tests.

Elragi (2000) also tested cube EPS blocks of 0.6 m dimensions using a free standing servo – hydraulic loading system. An EPS 29 (1.8 lb/ft^3) density block was loaded at a strain rate of 10% per minute and Young's moduli values were obtained. The deformation of the block was measured at different locations and modulus values ranging from 1.2 MPa (at interface of loading platen) to 18.1 MPa (middle of the block) were observed. A total average modulus for the block was taken to be 9.3 MPa (1349 psi). In addition, four stacks of a similar type and dimension of EPS blocks were tested at a strain rate of 2% per minute and moduli values ranging from 10.6 MPa (at interface) to 15.9 MPa (middle) were found. An average Young's modulus of 13.1 MPa (1900 psi) was considered for the entire stack of blocks. The Young's modulus values found from the V – Meter testing for an EPS 29 block range from 14.1 MPa (2049 psi) to 25.9 MPa (3760 psi). The values from the loading system for this density are slightly lower than the values from the V – Meter testing program. EPS 15 blocks of 0.6 m were also tested by the loading frame system and Young's modulus values were obtained. The Young's modulus values calculated for the similar density EPS blocks from the V – Meter testing program lie in close range with findings from the servo – hydraulic loading system, as shown in Figure 6.3.

Back calculated Young's modulus values from EPS 20 type geofoam blocks placed in Interstate 15 reconstruction project in Salt Lake City also presented values that lie within range forwarded by the V – Meter testing (Negussey, Stuedlein, Bartlett, & Fransworth, 2001). These values are shown in Figure 6.3. In addition, the relationship provided in Equation 5 presents values that are within range of values presented from the V – Meter testing program.

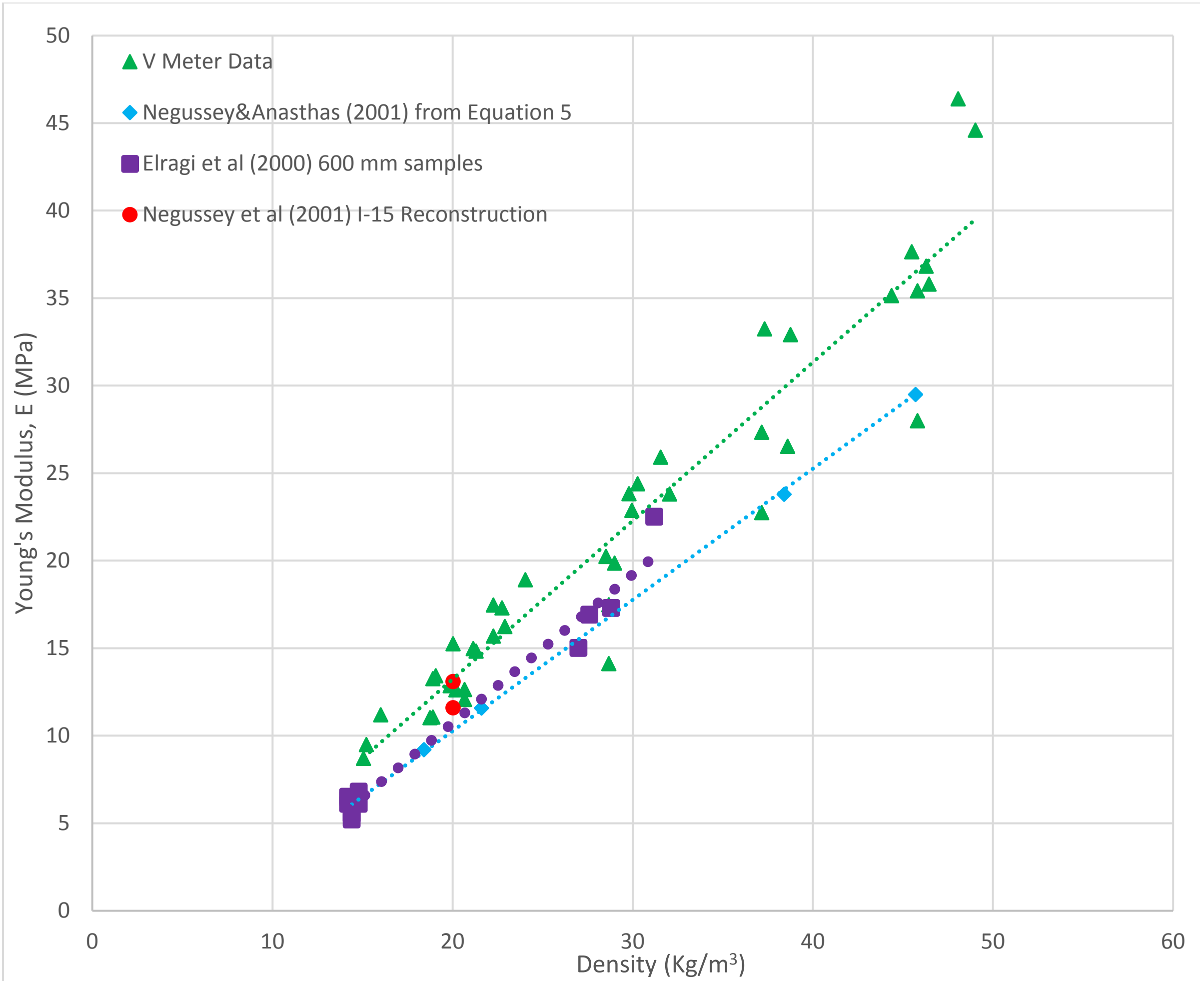


Figure 6.3 Young's modulus comparison with large sample testing

Figure 6.4 compares Young’s modulus values derived from settlement observations of EPS geofoam embankment and from lab testing of small EPS geofoam samples from the Interstate 15 project. The results are in accordance with the findings shown in Figure 6.2.

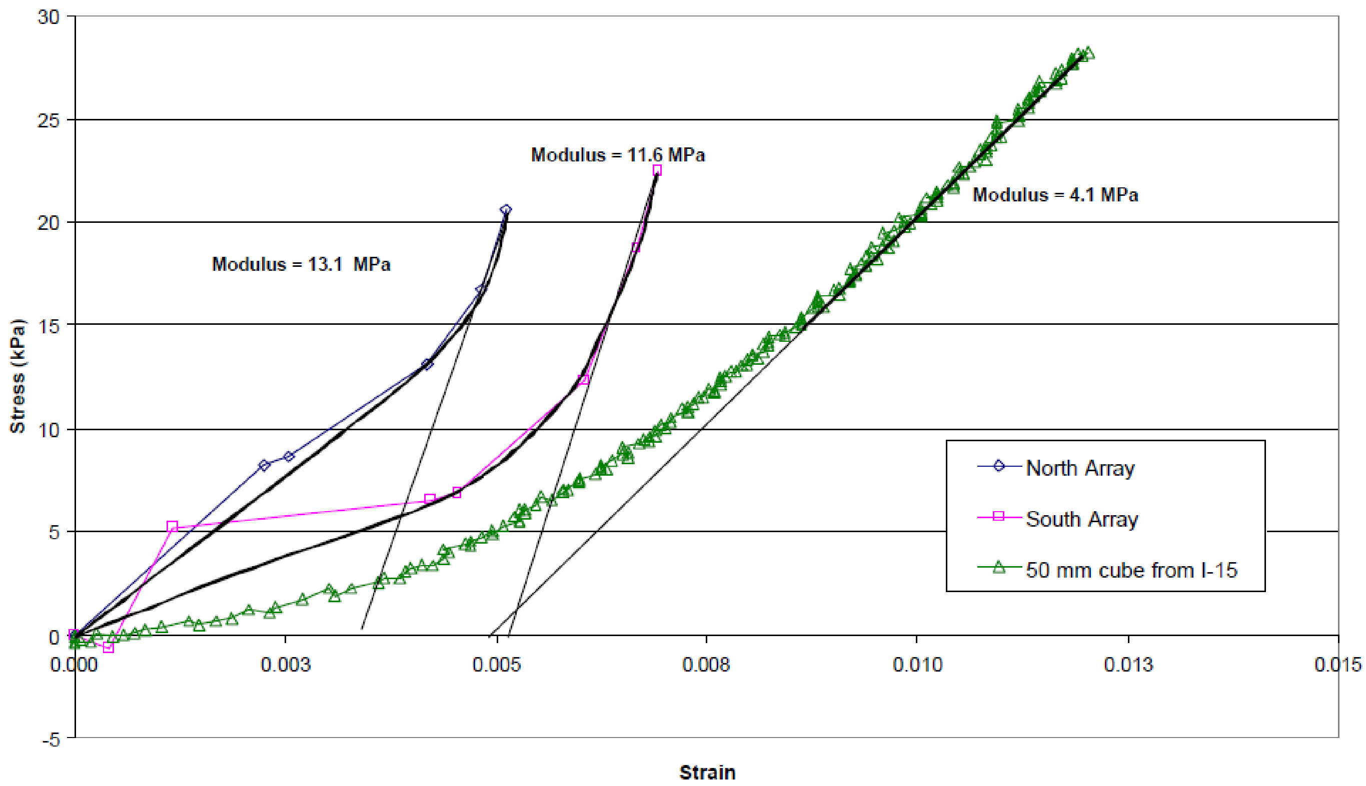


Figure 6.4 Young's modulus values derived from Interstate 15 reconstruction monitoring

(Negussey, Stuedlein, Bartlett, & Fransworth, 2001)

The transducers used in this NDT have a diameter of 50 mm and were used for testing small size samples to full size EPS blocks. The velocity readings obtained from smaller samples contained more variations than full size blocks of the same density. In addition, small sample testing involves cutting and trimming out samples from full sized blocks, which is considered as destructive testing. Hence, there is no need to perform NDT on small samples.

6.2 Comparison of modulus with other materials

The Young's modulus for EPS geofoam was compared with steel, timber, glass, concrete, and solid polystyrene (Beer, Johnston, & DeWolf, 2006). The Young's modulus value for solid polystyrene was again verified with other reference (Oral, Guzel, & Ahmelti, 2012). Three EPS geofoam blocks (16, 32, and 48 Kg/m^3) that have a high Young's modulus value from the V – Meter testing program are compared below in Table 6-2.

Table 6-2 Young's moduli comparison

Material Type	**Density, kg/m^3 (lb/ft^3)**	**Young's Modulus, GPa (ksi)**
EPS Geofoam (from Plant 1)	15 (0.9)	0.01 (1.3)
EPS Geofoam (from Plant 1)	32 (2.0)	0.03 (3.7)
EPS Geofoam (from Plant 4)	49 (3.0)	0.04 (6.4)
Solid Polystyrene	1030 (63.8)	3.1 (449.6)
Red Oak Timber (Air Dry)	660 (40.9)	12.0 (1740.4)
Glass, 98% silica	2190 (135.7)	65.0 (9427.4)
Concrete, Medium Strength	2320 (143.8)	25.0 (3625.9)
Reinforcing Steel, Medium Strength	7860 (487.3)	200.0 (29007.6)

The P wave velocity was estimated using concrete and large EPS geofoam sample compression data. Concrete cube samples with edge dimensions of 15 cm and cylindrical samples that are 30 cm long and 15 cm in diameter were tested in compression (Azenha, Ramos, Aguilar, & Granja, 2012). The concrete samples tested had an average density of about 2400 Kg/m^3 (150 lb/ft^3) (ρ_2) and Young's modulus value of 32.2 GPa (4670 ksi) (E_2). Compression data from Elragi (2000) on large (600 mm) EPS sample was used. A modulus value of 22.5 MPa (E_1) was obtained from compression tests on large EPS sample with density of 31.1 Kg/m^3 (1.9 lb/ft^3) (ρ_1). The following Mathcad calculation shows the velocities obtained (v_1 and v_2 are P wave velocity through of EPS geofoam and concrete, respectively).

Young's modulus obtained from large scale compression tests on EPS blocks (Elragi, 2000)

$$E_1 := 22.5\text{MPa}$$

$$\rho_1 := 31.1\,\frac{\text{kg}}{\text{m}^3}$$

Young's modulus obtained for concrete using compression tests on concrete blocks (Azenha et al, 2012)

$$E_2 := 32.2\text{GPa}$$

$$\rho_2 := 2400\,\frac{\text{kg}}{\text{m}^3}$$

P wave velocity estimation using compression data:

For EPS geofoam $v_1 := \sqrt{\frac{E_1}{\rho_1}} = 851\,\frac{\text{m}}{\text{s}}$

For concrete $v_2 := \sqrt{\frac{E_2}{\rho_2}} = 3663\,\frac{\text{m}}{\text{s}}$

The P wave velocity estimated for the large EPS geofoam sample (v_1) was within the ranges obtained for the same density in Table 5-1. From ultrasonic wave testing by using a 54 kHz probe, an average P wave velocity of 4014 m/sec (13170 ft/sec) was recorded by Azenha et al (2012) on the same concrete samples tested in compression. This value is comparable with the velocity estimated above (v_2) from the compression data. In addition, the V – Meter was used to obtain data on a cylindrical concrete specimen of 0.3 m height shown in Figure 6.5 in the laboratory. Twenty P wave velocity readings were taken and an average velocity reading of 3761 m/sec (12340 ft/sec) was obtained with 90% confidence level. The concrete cylinder has a density of 2179 Kg/m^3 (136 lb/ft^3). The average P wave velocity for concrete obtained in the V - Meter testing is in agreement with findings from Azenha et al (2012). This comparison, between EPS geofoam and the concrete specimen, is helpful in showing that the P wave velocity readings collected in the V – Meter testing can be used to estimate the Young's modulus values that are obtained from compression tests on large EPS samples.

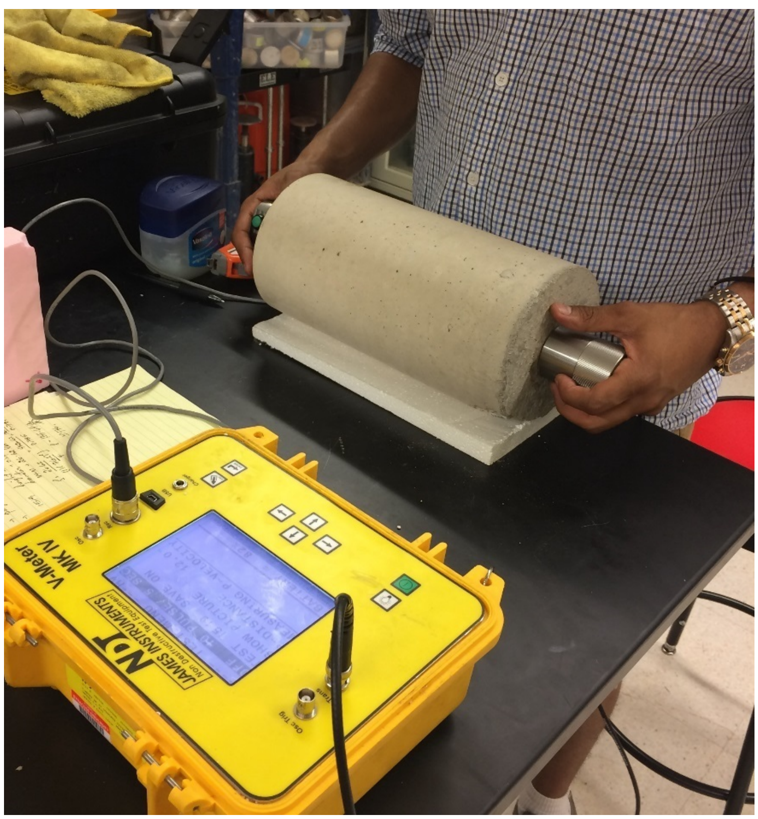


Figure 6.5 Concrete specimen of 0.3 m height tested using V - Meter in the laboratory

6.3 Confidence levels for moduli

The number of velocity readings required to get 80%, 90%, and 95% confidence level (CL) for the moduli obtained from the V – Meter testing are shown in Table 5-1. The underlined values indicate blocks that have met the confidence level criteria. Seven blocks meet the 95% CL, more than half of the blocks meet the 90% CL, and only 4 blocks do not meet the 80% CL criteria.

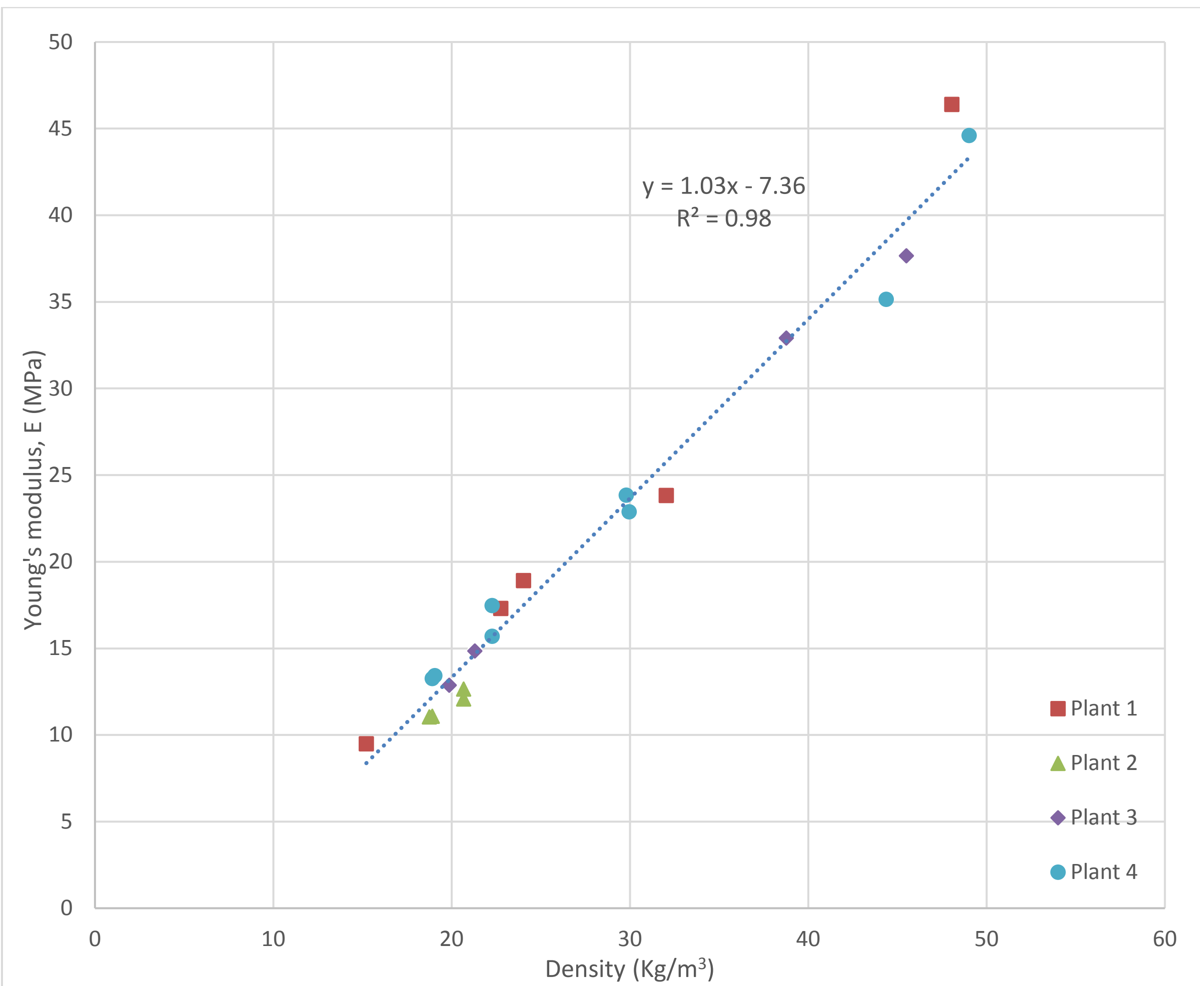


Figure 6.6 Measured density vs Young's modulus with 90% confidence level

Figure 6.6 shows the modulus values for EPS blocks which have number of velocity readings taken that are within 90% confidence level obtained from the V – Meter testing. The plot shows a high R – squared value from the modulus values plotted in Figure 6.1. The linear fit is in agreement with the theoretical relationship between density and Young's modulus shown in Equation 1.

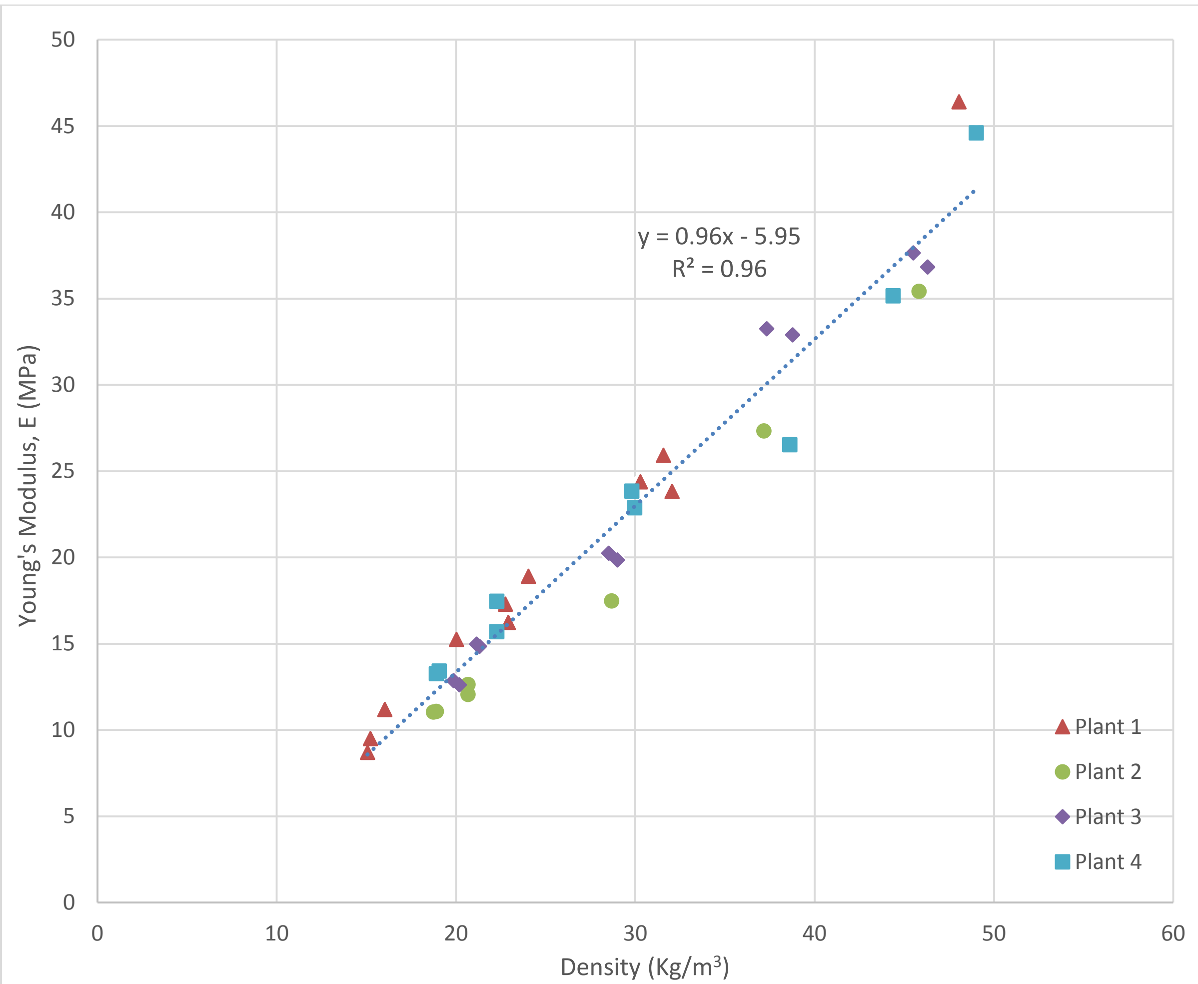


Figure 6.7 Measured density vs Young's modulus for 80% confidence level

Figure 6.7 shows the modulus values for EPS blocks with number of velocity readings taken that are within 80% confidence level. The plot also shows a high R – square value which is close to the one shown Figure 6.6.

By using the 90% and 80% CL values, the average velocity values shown in Table 6-3 can be recommended for EPS block densities.

Table 6-3 Average velocity ranges from the V – Meter testing program for EPS blocks

Nominal Density, kg/m^3 (lb/ft^3)	**Average Velocity Range, m/sec (ft/sec) for 90% CL**	**Average Velocity Range, m/sec (ft/sec) for 80% CL**
16 (1.00)	790 (2592)	760 – 833 (2496 – 2744)
20 (1.25)	765 – 840 (2512 – 2754)	765 – 873 (2512 – 2864)
24 (1.50)	765 – 890 (2508 – 2912)	765 – 890 (2508 – 2912)
32 (2.00)	865 – 895 (2830 – 2936)	780 – 907 (2562 – 2975)
40 (2.50)	890 – 922 (2921 – 3024)	830 – 945 (2721 – 3098)
48 (3.00)	910 – 985 (2986 – 3225)	880 – 985 (2886 – 3225)

6.4 Resin bead comparison

Information on resin beads used to produce the EPS geofoam blocks for this testing program was provided by the molding plants. The resin bead types and suggested end product density recommendations are provided in Table 6-4.

Table 6-4 Polystyrene resin beads used by manufacturing plants

EPS geofoam manufacturers	Used Bead		Geofoam density (Nominal) produced (Kg/m³)	Recommended Density Range (Kg/m³)
	Bead Manufacturers	Bead Type		
Plant 1	Flint Hills Resources	3454	32	14 - 20
		S5454	48	14 - 32
		5454	16, 24	14 - 20
	Styropek	BF395	16, 16R10	14 - 24
	Nova Chemical	M77BLV	32	19, 14, 14*
	NexKemia	M444D	20	16
		M464D	16R10, 32, 24	14
Plant 2	Nova Chemical	33MBHD	16, 16R30	22, 14, 14*
		M77BG	20, 20R30, 24	35, - , 20*
		M77CG	24R30, 32, 32R30, 40, 48	, - , - , 20*
Plant 3	Flint Hills Resources	S3454	16, 16R15, 20R15	14 - 20
		S7454	32, 40, 48	18 - 40
	NexKemia	M444D	24, 24R15	16
		M464D	16, 20	14
Plant 4	Styro-Chem	MB500E	16, 20	14**
		MB590L	24, 32, 38, 46	19**
	Styropek	BF395	16, 16R15	14 - 24
	NexKemia	MG64D	16R35	14
	Flint Hills Resources	I5354	38	24 - 48
		S5454	40	14 - 32

Note: * Nova Chemicals suggest three densities depending on expansion method used as: Single Pass Continuous, Double Pass Continuous, and Batch.
** Styro–Chem recommend minimum density values.
The "R" in Geofoam Density Produced column indicates EPS geofoam block with regrind content (e.g. 16R10 indicates 10% regrind content in 16 Kg/m³ nominal density EPS block).

The bead types underlined in Table 6-4 indicate resin beads that were not used for the suggested density of geofoam as per the recommendation of the resin bead manufacturers. Plant 1 used bead types 3454 and M77BLV to produce 32 Kg/m^3, S5454 and 5454 bead types to produce 24 and 48 Kg/m^3 EPS density blocks, and M444D bead type to produce 20 Kg/m^3 and M464D bead type to produce blocks of 24 and 32 Kg/m^3 nominal densities, respectively; outside of the recommended density range. Plant 2 used bead type M77CG to produce 32, 40, and 48 Kg/m^3 nominal density EPS blocks; outside the recommended density range by Nova Chemicals. Plant 3 used bead type S7454 for 48 Kg/m^3 nominal density, bead types M464D and M444D to produce 20 and 24 Kg/m^3 EPS density blocks, respectively; which are outside the recommended density range. More data on resin bead properties provided by the manufacturers are shown below in Table 6-5.

Table 6-5 Polystyrene resin bead properties

Bead Type	Bead Grade	Bead Manufacturer	Typical Unxpanded Bead Size (mm)	Recommended ASTM C-578 Type - and End Use application	Pentane Content (%wt)
3454	Modified	Flint Hills Resources	0.9 - 1.25	I, VIII	4.7±0.4
5454			0.9 - 1.25	I, VIII, II	4.8± 0.3
S3454			1.1 - 1.7	I, VIII	4.7±0.4
S5454			0.7 - 1.4	VIII, II, IX	4.8±0.3
S7454			0.4 - 0.8	II, IX, XIV	4.8± 0.3
I5354			0.7 - 1.4	I, VIII, II, IX, XIV, XV	3.5±0.3
M464D	Modified Standard	NexKemia	0.6 - 1.1	Insulation type I & II, ICF's, fabricated packaging, SIP's	6.4
MG64D	Modified Geofoam		0.5 - 2.0	Geotechnical Projects	6.5
M444D	Modified Type II Application		0.6 - 1.1	Insulation type II & IX, ICF's, SIP's fabricated packaging	4.4
33MBHD	Modified	Nova Chemicals	0.85	Insulation, SIPs, ICFs, Fabricated Packaging, Geofoam	5.2
M77BG	Low Pentene Modified		0.85	High Density, Types XIV and XV, Geofoam	3.8
M77BLV			0.85	Insulation, SIPs, ICFs, Fabricated Packaging, Geofoam	4.5
M77CG			0.6	Insulation, ICFs, Fabricated & Custom Packaging, Lamination, Geofoam	4.5
BF395	Modified	Styropek	0.6 - 1.18	Block molding applications, mid-range and high densities, thickness of wall >8 mm, with excellent fusion and surface appearance. Shape molding applications for machines without vacuum system and excellent cycle time.	5.5 - 6.4
MB500E		Styro-Chem	0.9		5.9
MB590L			0.9		4.9

<u>Note</u>: Flint Hills Resources, NexKemia, and Styropek provide a range for resin bead diameters. Nova Chemicals and Styro-Chem provide a nominal diameter for resin beads.

Table 6-5 shows the resin bead diameters and respective pentane content by % weight. Table 6-5 shows recommended densities decrease with increasing pentane content. In addition, the two NexKemia beads M444D and M464D are not recommended for geotechnical applications. Furthermore, the MB590L bead type contains a medium pentane content which is not suitable for production of high density EPS blocks.

6.5 Factors affecting velocity consistencies for EPS geofoam

As shown in the P wave velocity data that was provided in the previous chapter, velocity of up to 333 m/sec (1100 ft/sec) were observed. Moreover, the noted variations from the respective mean velocities do not depend on EPS geofoam density. The possible causes for these variations are discussed below.

6.5.1 Resin bead types and sources

EPS geofoam block densities that resulted in average velocity ranges greater than 45 m/sec (150 ft/sec) and coefficient of variation greater than 1%, shown in Table 5-1, were generally found to be produced from resin bead types that were not recommended for that nominal density. The exception were the 16 Kg/m^3 density block at Plant 1, the 37.3 Kg/m^3 density block from Plant 3, and 38.6 and 46.5 Kg/m^3 density block from Plant 4.

In general, the higher the pentane content in resin beads, the lower the density of EPS block to be produced. The pentane content in resin beads is essential for expansion of the beads to pre puffs. Achieving the required per puff expansion and pentane content is in turn essential in obtaining the required EPS geofoam density. Hence, when the appropriate resin beads are not used, the expected density may not be uniformly attained.

EPS geofoam manufacturers mainly consider compatible price, performance with the molding equipment, and the density recommendations when purchasing resin beads. The price for a resin bead may be affected by the storage duration after production and the price of crude oil in the market. Using resin beads for a density which is not recommended may result in more non uniform EPS geofoam blocks and wider range of P wave velocities for the block.

6.5.2 Pentane Loss

Pentane loss during storage is also another factor to be considered. Shelf life of resin beads is dependent on the type of storage facility (BASF, 1995). If sealed steel drums are used, the recommended storage life is six months. On the other hand, if porous fiber board containers are used, the recommended storage life comes down to one month. Storage requirements of resin beads in Europe specify containers to have an inner plastic liner as a barrier against pentane loss (Plastics Europe, 2007). From the field testing program in this research, it was observed that the resin beads are transported in fiber board sacks that have plastic membrane inner lining as shown in Figure 1.1. If resin beads are not used within the appropriate shelf period as per the resin bead manufacturer’s recommendation, loss in expansion capacity can result. Plant 4 indicated their resin beads perform efficiently for up to 12 months and that low pentane content beads can perform well even after 2 years of storage. This suggestion is not consistent with the recommendation of BASF (BASF, 1995). Resin bead suppliers mention the effect of one or two step process of adding the blowing agent (whether the blowing agent is added during polymerization or after polymerization and after the resin bead is produced) in affecting the shelf life of the resin bead.

The pre expansion process of the resin beads into pre puffs is also another production segment of pentane loss. The pre puffs undergo intermediate aging to allow drying and normalization with atmospheric pressure. The normalization process takes around 12 hours. However, pre puffs that undergo further expansion to achieve low density EPS geofoam need to be aged for only 4 to 8 hours (BASF, 1998). Thus pre puffs expanded to produce low density EPS geofoam blocks require aging for a shorter time period to incur less pentane losses. Whereas, pre puffs for high density blocks need to be aged longer to allow more pentane loss. EPS geofoam manufacturers age pre – expanded beads or pre puffs for more than 24 hour durations for high densities. During expansion of resin beads to pre puffs and aging for 24 hours, an average 24% and 19% of original pentane content in resin beads is lost respectively (EPA, 1990). Estimates of pentane loss percentages in the EPS block manufacturing stages are presented in Table 6-6. Even if the appropriate resin beads are used, prolonging or shortening the pre puff aging can affect the EPS geofoam block density. This can in turn affect the P wave velocity consistency through the block.

Table 6-6 Pentane loss in EPS block production *(EPA, 1990)*

Pentane Loss	**% Lost During Expansion**	**% Lost During 24 Hrs. Storage of Pre Puff**	**% Loss During Molding**	**% Lost 1st 24 Hours after Molding**	**% Lost 2nd 24 Hours after Molding**
Average	24	19	14	15	13
Range	10 – 44	5 – 37	4 – 31	5 – 30	3 – 23

6.5.3 Non homogeneity in EPS blocks

Previous tests performed on small samples from a full EPS geofoam block have shown variability in bulk density of up to 25% (Eriksson & Trank, 1991). The range in bead diameters for a specific resin bead type may also present a source for velocity inconsistencies, particularly if segregation develops during handling. As indicated in Table 6-5, resin beads from Flint Hills Resources, NexKemia and Styropek have a range associated with resin bead diameters while Nova Chemicals and Styro-Chem only provide nominal diameters. During the expansion process, different bead diameters result in a varying size of pre puffs that in turn result in less homogenous EPS blocks.

The steaming employed during the molding of an EPS geofoam block may result in direction dependent shrinkage on the block (BASF, 1994). EPS block manufacturing plants employ two types of molds, conventional and vacuum. Thus, the EPS production equipment also has a major part in affecting the EPS geofoam block property. However, additional data pertaining to EPS geofoam blocks molded from both type of molds must be collected to draw further relationships. The resin bead diameter and type of production equipment may explain some of the variance in velocities shown in Table 5-1. These variables have not been considered in previous studies of EPS block uniformity and engineering properties.

6.5.4 Regrind content

EPS geofoam blocks with regrind or recycled contents ranging from 10% - 35% were tested in the V – Meter testing program. P wave velocities were not obtained from the majority EPS blocks with regrind content in tests without amplifier. A comparison of the data collected from Plant 1 indicates that there is a difference in P wave velocities between a virgin 16 Kg/m^3 (1 lb/ft^3) EPS geofoam nominal density block and one containing a 10 % regrind but of the same density. While velocities ranging from 760 – 836 m/sec (2496 – 2744 ft/sec) were obtained in three blocks of 16 Kg/m^3 (1 lb/ft^3) density virgin blocks, velocities ranging from 728 – 810 m/sec (2391 – 2655 ft/sec) were collected using a signal amplifier on two other blocks of the same density but with 10% regrind, as shown in Table 5-2. Using the velocities in Table 5-2 and nominal densities, the Young's modulus values shown in Table 6-7 were obtained. Amplifying the signal resulted in less than 5% increase in Young's modulus values except for the 16 Kg/m^3 (1 lb/ft^3) virgin block which increased by 11%. For the same 16 Kg/m^3 (1 lb/ft^3) EPS density block, a decrease in modulus ranging from about 16% – 25% occurred for blocks containing regrind as shown in Table 6-7. This value is in agreement with previous findings (Negussey, Srirajan, & Anasthas, 2001). The moduli obtained with the amplified and non-amplified signals are also shown in Figure 6.8.

Table 6-7 Young's modulus comparison for amplified and non-amplified signals performed at Plant 1

Block	Density, Kg/m^3 (lb/ft^3)	Young's Modulus E, MPa (psi)		
		Without Amplification	X4 Amplification	X7 Amplification
1	16 (1.00) (w/ 10% regrind)	0	9.4 (1365)	9.4 (1365)
2	16 (1.00) (w/ 10% regrind)	0	10.5 (1520)	8.5 (1233)
3	16 (1.00)	11.5 (1664)	12.5 (1809)	12.5 (1808)
4	20 (1.25)	15.2 (2211)	15.8 (2291)	15.9 (2303)
5	24 (1.50)	18.9 (2743)	19.8 (2865)	19.8 (2873)
6	32 (2.00)	24.1 (3491)	24.7 (3588)	24.9 (3615)
7	48 (3.00)	46.4 (6729)	46.8 (6792)	46.9 (6800)

A 32 Kg/m^3 (2 lb/ft^3) nominal density EPS block with a 30% regrind content tested at Plant 2 showed a much lower velocity of 707 m/sec (2320 ft/sec) while the virgin block for the same nominal density showed a reading of 780 m/sec (2562 ft/sec). This decrease in velocity by about 9.4% results in about 18% decrease in Young's modulus. This value is lower than the 25% decrease in Young's modulus obtained from an unconfined compression test for an EPS 15 type geofoam containing 30% regrind (Negussey, Srirajan, & Anasthas, 2001). For the same percentage of regrind content, the reduction in Young's modulus decreased with increasing density. Hence, reduction in mean P wave velocities and higher variability in velocity readings can be attributed to the presence of regrind in EPS geofoam blocks.

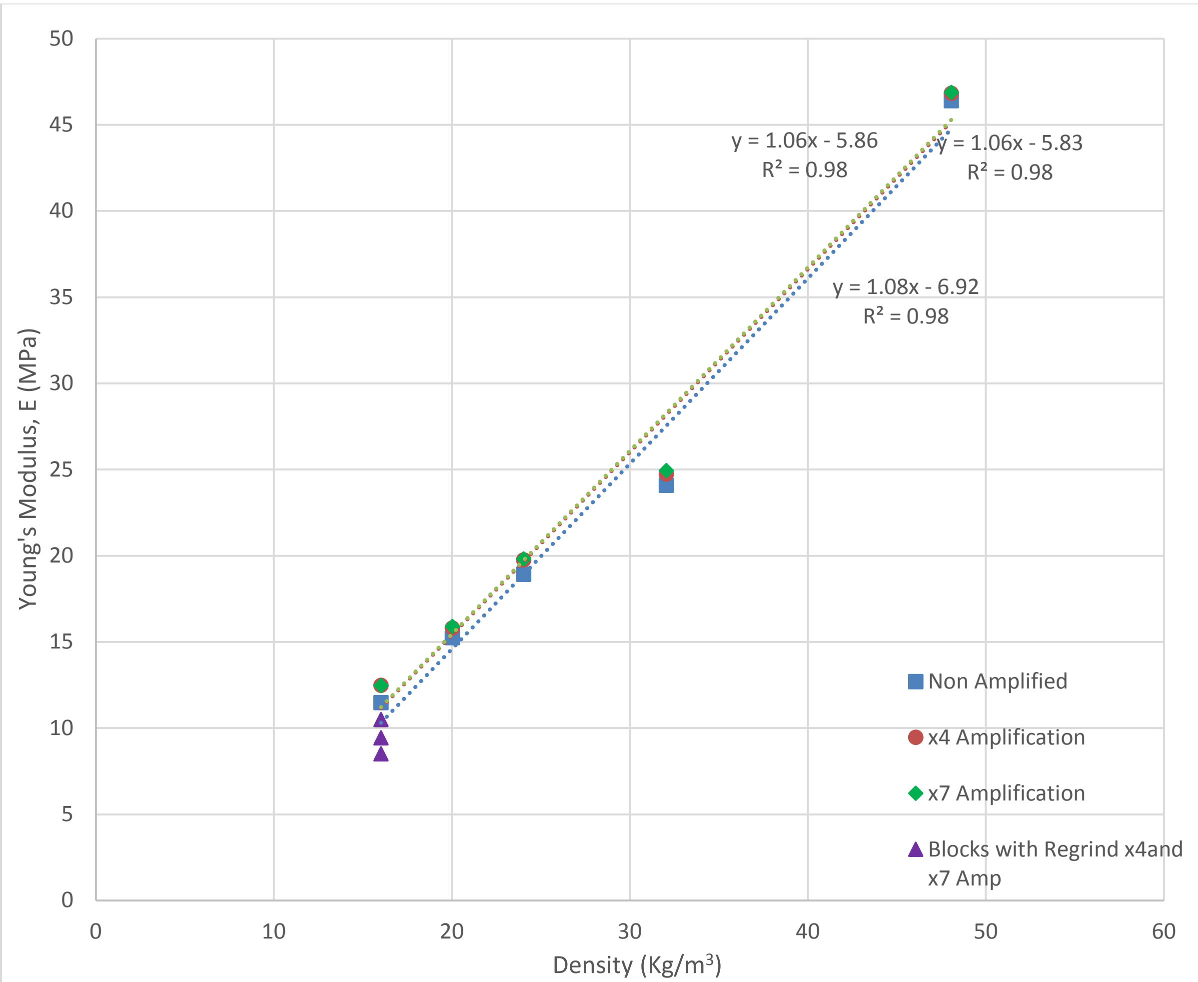


Figure 6.8 Young's modulus comparison with signal amplification from tests at Plant 1

Figure 6.8 shows comparison of Young's moduli obtained with and without amplified signals. A maximum of 8% increase was obtained with amplification for the 16 Kg/m^3 (1 lb/ft^3) density block. Figure 6.8 also shows low modulus values for EPS blocks containing regrind as compared to virgin blocks of the same density. P wave amplitude levels may be related to regrind content in EPS geofoam blocks of the same density.

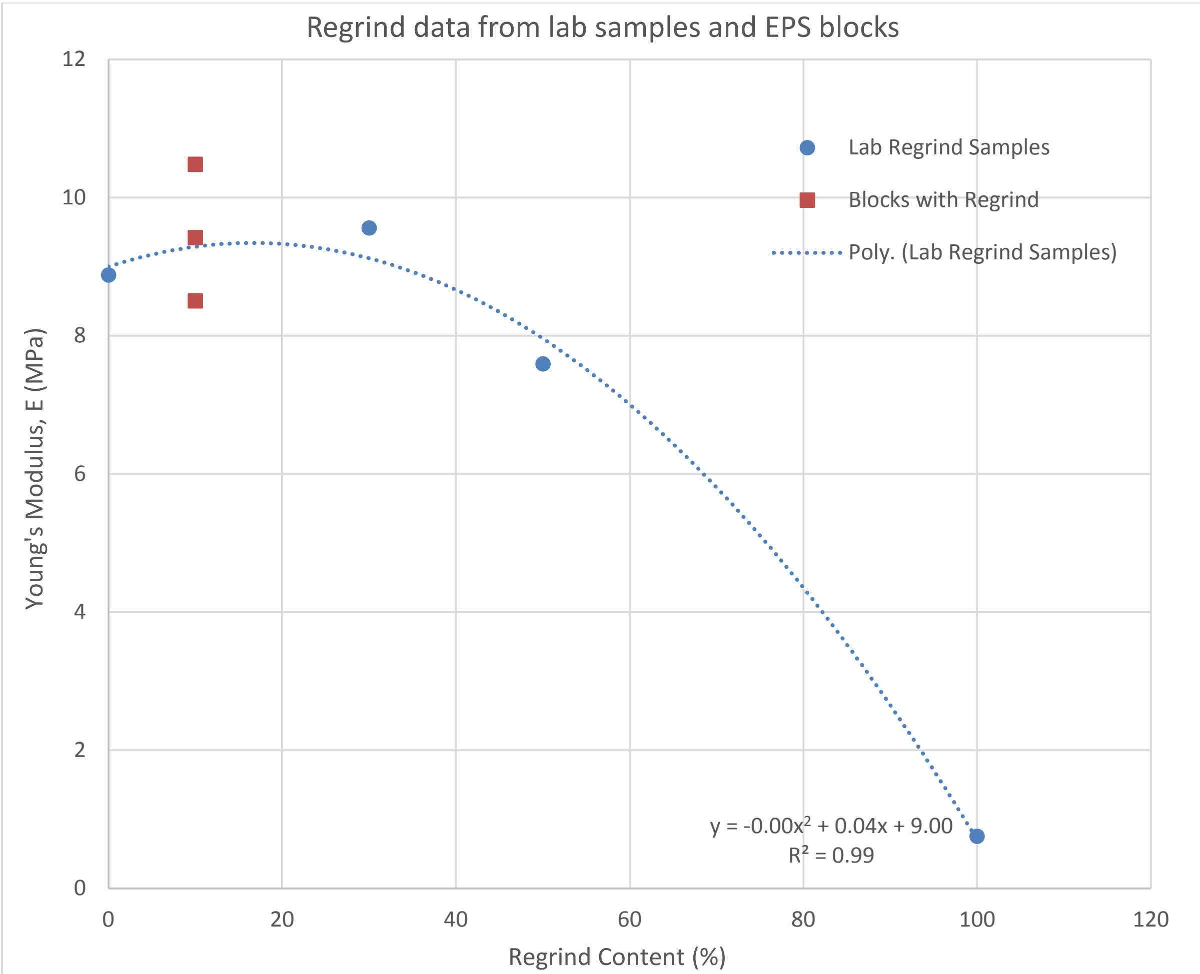


Figure 6.9 Regrind content vs Young's modulus for 90% CL of lab samples and EPS blocks tested with amplifier at Plant 1

The modulus for the lab samples with regrind content indicated in Table 3-2 are plotted in Figure 6.9. Young's modulus values of 8.9 MPa (1290 psi), 9.6 MPa (1390 psi), 7.6 MPa (1100 psi), and 0.8 MPa (110 psi) are obtained for samples containing 0%, 30%, 50%, and 100% regrind respectively. EPS blocks containing up to 30% regrind do not indicate degradation in Young's modulus compared to the virgin block of the same density.

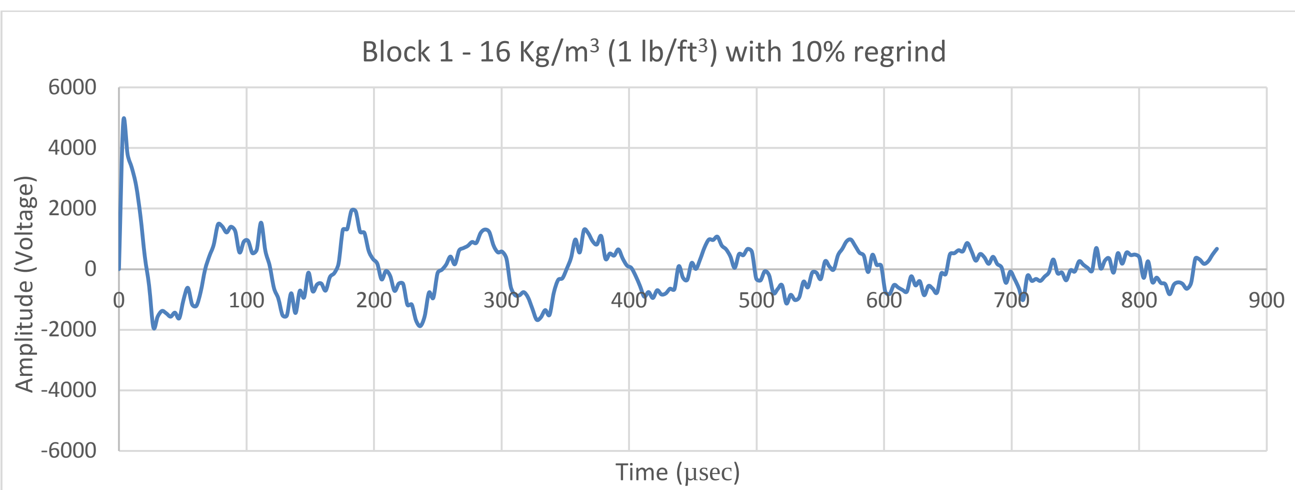
6.6 Wave properties

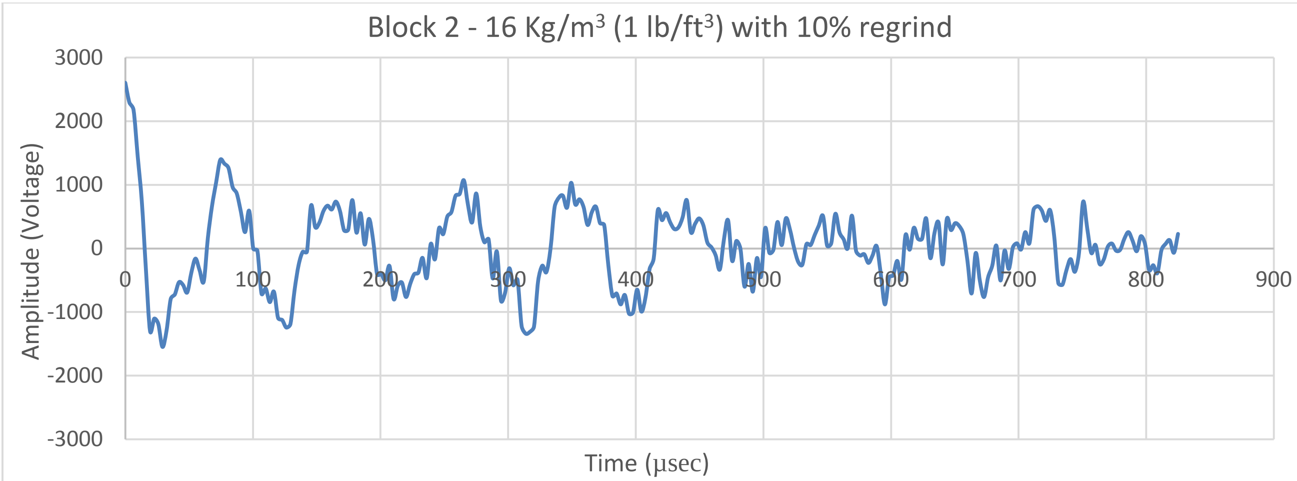
The P wave used in this investigation has a frequency of 54 kHz. A maximum amplifier gain of 500 was used and 1 kV was supplied to the transmitter energizing pulse. The second round tests at Plant 1 showed that the 16 Kg/m^3 (1 lb/ft^3) nominal density virgin (on 1.2 m width) and one containing 10% regrind EPS block did not transmit the P wave signal, as shown in Table 5-3. However, signal was detected with the 4 and 7 times magnification of the P wave amplitude. The data collected with and without using the amplifier show that the P wave amplitude, travel length, and regrind content damping affect the signal detection.

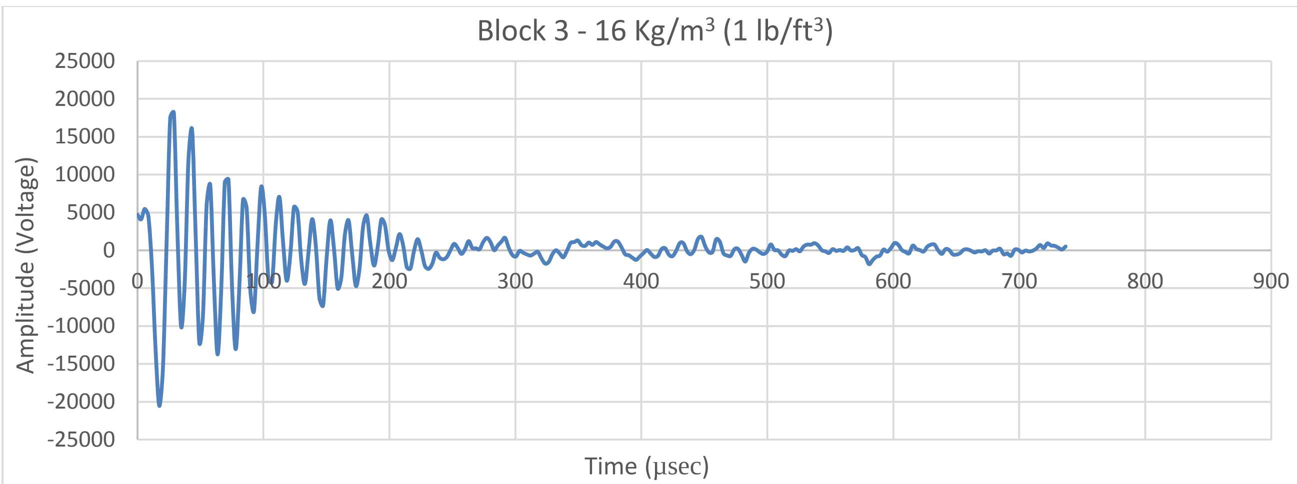
Amplitudes of amplified and non-amplified signals were plotted against time. Smooth curves were obtained from the amplified signals. The amplitude profiles shown in Figure 6.9 were obtained from the P wave tests performed using the x7 amplification on the 0.6 m thickness (H3) of the EPS blocks.

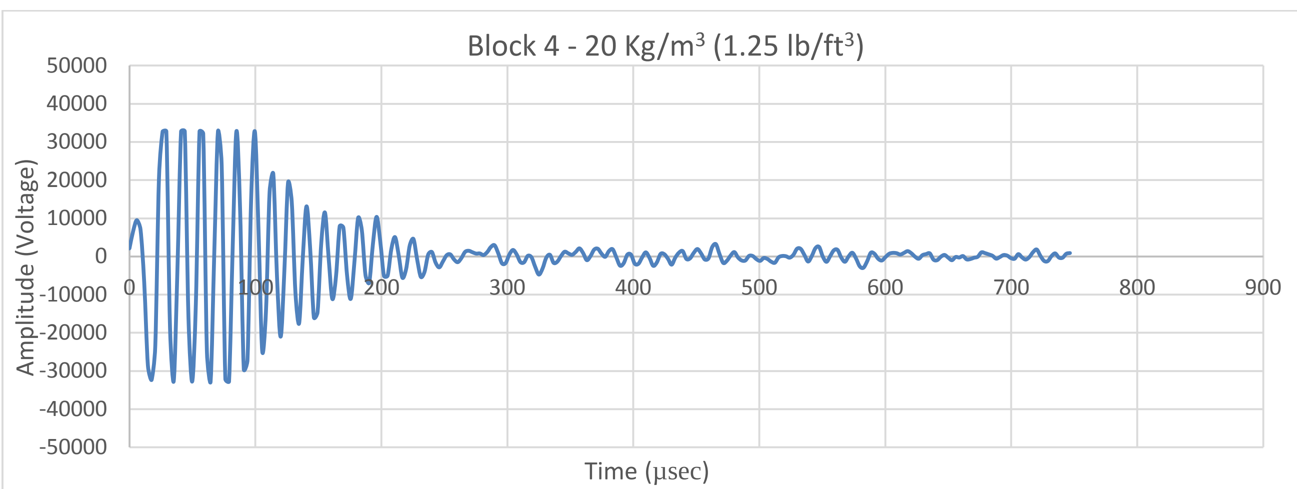
As shown in Figure 6.10, the P wave duration was longer with a decrease in density with the longest being in the blocks containing regrind. However, the peak amplitude duration increased with density. The maximum amplitude transmitted in the 16 Kg/m^3 (1 lb/ft^3) nominal density blocks containing 10% regrind were about 10 times lower than the cutoff amplitude value in the 20, 24, 32, and 48 Kg/m^3 (1.25, 1.5, 2, and 3 lb/ft^3) nominal density blocks. The maximum amplitude transmitted in the 16 Kg/m^3 (1 lb/ft^3) nominal density virgin block was about 2 times lower than the cut off amplitude value in the higher density EPS blocks. The maximum amplitude transmitted in the 16 Kg/m^3 (1 lb/ft^3) nominal density blocks containing 10% regrind were about 5 times lower than the maximum amplitude in the virgin block of the same density. As a result, EPS blocks containing regrind can be identified from the time history plot of the P waves. This finding is in accordance with the findings stated in the vibration reduction application of EPS geofoam (Radhakrishnan & Negussey, 2011) where by low density EPS blocks are more efficient in damping wave amplitudes than higher density blocks. In addition, low density EPS blocks with regrind content can serve as better dampers than virgin blocks of the same density.

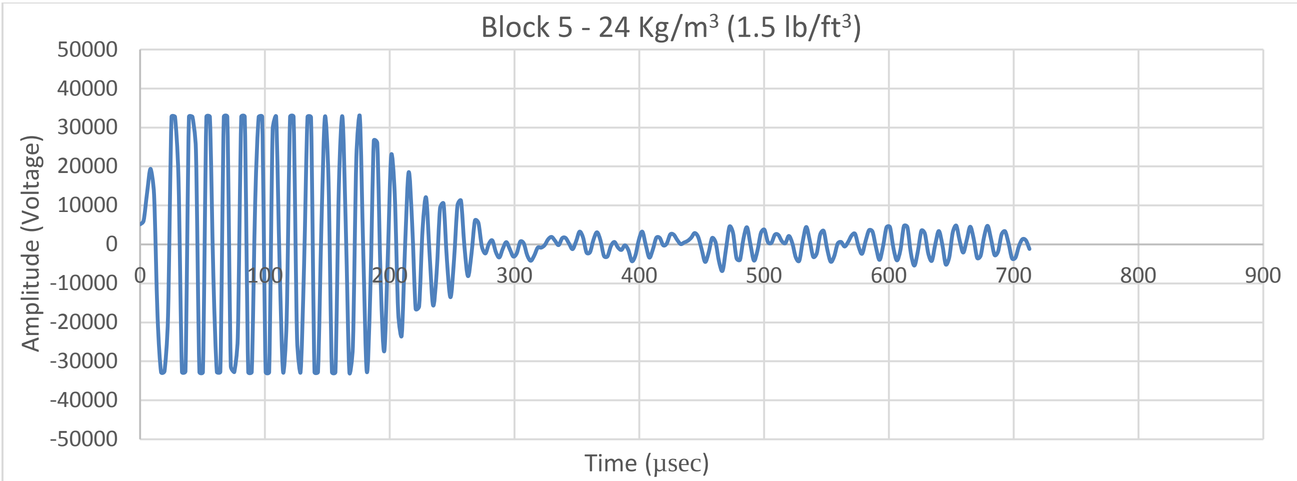
The wavelength of the P wave was obtained by dividing the average velocities obtained by the frequency of the transducers used. There seems to be an interference in P wave transmission indicated by peaks and valleys with in a period as shown in the amplitude vs time profiles for Blocks 1 and 2 (blocks containing regrind) in Figure 6.10. Hence, it was difficult to determine the actual wavelengths for these blocks. Small values for wavelengths of about 20 mm and 15 mm were obtained for the virgin 16 and 48 Kg/m^3 (1 and 3 lb/ft^3) nominal densities, respectively.

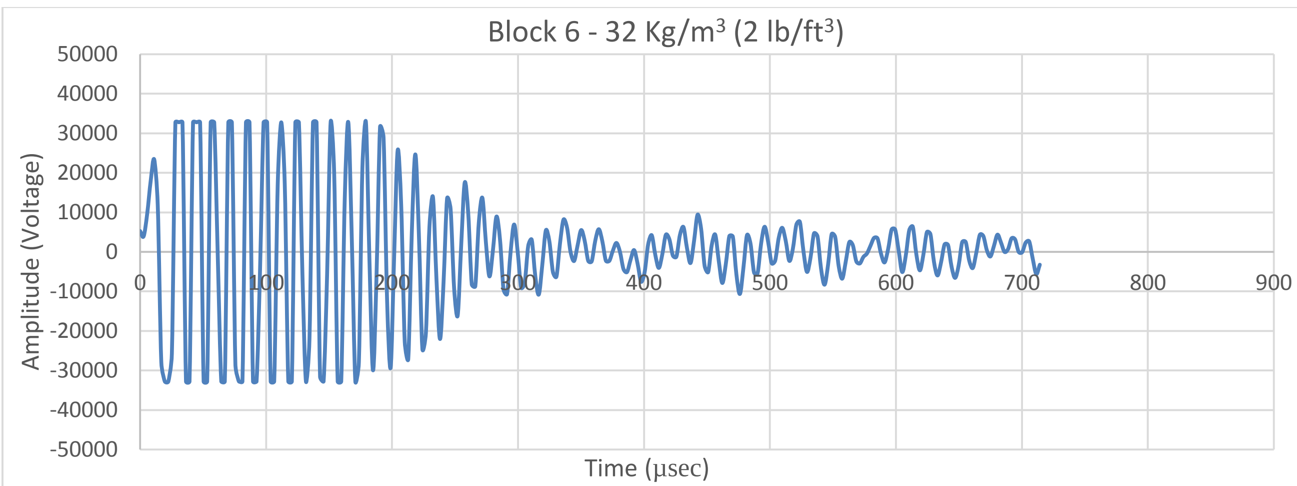



Block 2 - 16 Kg/m3 (1 lb/ft3) with 10% regrind
Amplitude (Voltage)
3000
2000
1000
0
-1000
-2000
-3000
0
100
200
300
400
500
600
700
800
900
Time (µsec)


Block 3 - 16 Kg/m3 (1 lb/ft3)
Amplitude (Voltage)
25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
0
100
200
300
400
500
600
700
800
900
Time (µsec)


Block 4 - 20 Kg/m3 (1.25 lb/ft3)
Amplitude (Voltage)
50000
40000
30000
20000
10000
0
-10000
-20000
-30000
-40000
-50000
0
100
200
300
400
500
600
700
800
900
Time (µsec)





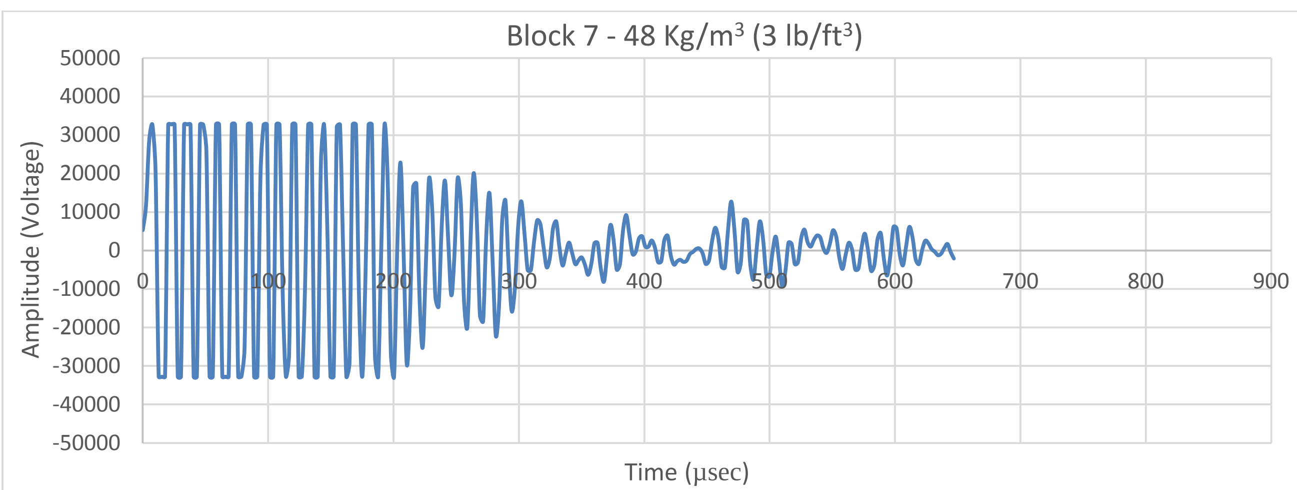


Figure 6.10 Amplitude comparisons for the same location (H3) on different density blocks at Plant 1 using x7 amplification

7 Conclusions and Recommendations

7.1 Conclusions

From the testing program in this research, the following can be concluded.

1) The V – Meter testing program presents a practical on-site, environmentally friendly and energy saving, and sustainable quality assurance method. The testing program can be conducted by one person with a mounting frame to fix transducers on the required locations around the EPS geofoam block. The V – Meter is an affordable instrument and can be used by the contractor and / or supplier in addition to third party companies.

2) The current means by which EPS geofoam homogeneity and strength properties are checked is by using destructive testing that is time consuming and expensive in the long term. The sample selection method involves trimming 6 samples per block as per ASTM, European, Norwegian, and Japanese standards from prescribed locations. The method does not represent a statically acceptable random sampling of the full EPS geofoam block. In addition, the six samples selected represent about 0.01% of the entire block volume. This destructive sampling and testing method is usually not required or not performed for almost all projects. The more common and sustainable form of quality assurance on site is to check the weight of full size blocks only. V – Meter testing can be used as a replacement for and / or a reduced destructive method with random sampling. Also, due to the easy application of the V – Meter testing, more blocks can be

tested resulting in a more efficient and tightened quality assurance program without or much reduced waste and less environmental impact.

3) In using V – Meter testing program as a means of quality assurance, the velocity range in a full block can be helpful identifying areas of inhomogeneity and possible strength inconsistencies. In this testing program, by setting an allowable velocity range of 45 m/sec (150 ft/sec) and a confidence level greater than 90% within an EPS block, Young's modulus values that are within 35 kPa (5 psi) and 100 kPa (15 psi) range are obtained for full EPS blocks of 16 and 48 Kg/m^3 (1 and 3 lb/ft^3) nominal densities, respectively. Hence, by setting the allowable range and confidence level for the P wave velocity data within an EPS block, the quality for any given density of EPS can be assured.

4) The Young's modulus values derived from the design compressive resistance (at 1% strain) values put forward for EPS geofoam blocks in the ASTM D6817/6817M – 15 do not represent realistic values. These values should at best be considered as index parameters and should be revised to accommodate the high modulus values for large size samples and full EPS geofoam blocks.

5) The relationship between P wave velocity through an EPS block and density of the block cannot be easily understood without accounting for the Young's modulus of the block. The Young's modulus, however, has a clear dependency on density. Accepting lower density EPS blocks is accepting lower Young's modulus. Hence, it is important to ensure

the specified density is achieved. In small projects, paying EPS manufacturers by weight of the required EPS geofoam blocks supplied instead of the current practice of using volume as payment may serve as an incentive to get blocks with expected moduli. To assure delivery of a desired density, payments can be restricted to the nominal and ± 10% of the nominal density.

6) The velocities shown in Table 6-3 indicate a range and an increasing trend with standard production density. Using the average velocity for each range and the nominal density, lower limits of Young's modulus values for EPS geofoam blocks are provided in Table 7-1. Also shown are the low ASTM D6817/D6817M – 15 moduli determined at 1% strain in current practice.

Table 7-1 Recommended Young's modulus values for EPS blocks

Nominal Density, Kg/m^3 (lb/ft^3)	**Young's Modulus from V – Meter testing for 90% CL, min MPa (ksi)**	**Young's Modulus from ASTM D6817/D6817M - 15, min MPa (ksi)**
16 (1.00)	10 (1.4)	2.5 (0.4)
20 (1.25)	12 (1.7)	4.0 (0.6)
24 (1.50)	14 (2.0)	5.0 (0.7)
32 (2.00)	24 (3.6)	7.5 (1.1)
40 (2.50)	32 (4.6)	10.3 (1.5)
48 (3.00)	40 (5.8)	12.8 (1.9)

7) The presence of regrind exceeding 30% in an EPS geofoam block results in a significant reduction of Young's modulus from that of a same density virgin block. This has been confirmed by the lower velocity readings obtained from EPS geofoam small samples and amplifier tests on full sized blocks that contain significant regrind. Moreover, the inhibition of P wave transmission (longer P wave durations seen in blocks containing regrind in Figure 6.10) through EPS geofoam blocks with regrind content suggests the possibility of using blocks with regrind content for damping or barrier related applications.

7.2 Suggestions for future research

This research is focused on the use of acoustic P waves generated from the V – Meter Mark IV instrument to determine EPS geofoam block properties. Furthermore, this research has tried to show realistic values for Young's modulus values for full EPS geofoam blocks. However, supplementary research using S waves to better understand the shear modulus for EPS blocks need to be undertaken. By using the outcomes of this research and with the findings from the S wave testing, a better understanding of the Poisson's ratio for full EPS geofoam blocks can be gained.

The Thermal Resistance (R) value of EPS foams used for insulation is a number used to describe the property of an insulation material from the temperature difference between the warm and cold sides and the thickness of the insulation. R values for EPS foams increase with an increase in density. Homogeneity of the insulation material is of high significance and hence the V – Meter testing method can be used to serve as a quality and homogeneity check.

From previous parametric studies and modelling, the use of low density geofoam has resulted in good vibration amplitude reduction (Radhakrishnan & Negussey, 2011). By employing amplified signals and sensitive detection, the amount of wave amplitude reduction with regrind content can be optimized. The findings in this research indicate that EPS geofoam blocks with a high regrind content can perform better than virgin blocks in vibration damping. As a result, such additional research, may promote sustainability and environmental benefits from recycling.

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