Chapter 3
Geomembranes

This chapter focuses upon the manufacturing quality assurance (MQA) aspects of geomembrane formulation, manufacture and fabrication, and on the construction quality assurance (CQA) of the complete installation of the geomembranes in the field. Note that in previous literature these liner materials were called flexible membrane liners (FML’s), but the more generic name of geomembranes will be used throughout this document.

The geomembrane materials discussed in this document are those used most often at the time of writing. However, there are other polymer types that are also used. Aspects of quality assurance of these materials can be inferred from information contained in this document. In the future, new materials will be developed and the reader is advised to seek the appropriate information for evaluation of such new or modified materials.

3.1 Types of Geomembranes and Their Formulations

It must be recognized that all geomembranes are actually formulations of a parent resin (from which they derive their generic name) and several other ingredients. The most commonly used geomembranes for solid and liquid waste containment are listed below. They are listed according to their commonly referenced acronyms which will be explained in the text to follow. Other geomembranes in limited use or under initial field trials will also be mentioned where appropriate but will be covered in less detail than the types listed below.

Table 3.1 - Types of Commonly Used Geomembranes and Their Approximate Weight Percentage Formulations*

<table>
<thead>
<tr>
<th>Geomembrane Type</th>
<th>Resin</th>
<th>Plasticizer</th>
<th>Filler</th>
<th>Carbon Black or Pigment</th>
<th>Additives</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>95-98</td>
<td>0</td>
<td>0</td>
<td>2-3</td>
<td>0.25-1.0</td>
</tr>
<tr>
<td>VLDPE</td>
<td>94-96</td>
<td>0</td>
<td>0</td>
<td>2-3</td>
<td>1-4</td>
</tr>
<tr>
<td>Other Extruded Types**</td>
<td>95-98</td>
<td>0</td>
<td>0</td>
<td>2-3</td>
<td>1-2</td>
</tr>
<tr>
<td>PVC</td>
<td>50-70</td>
<td>25-35</td>
<td>0-10</td>
<td>2-5</td>
<td>2-5</td>
</tr>
<tr>
<td>CSPE***</td>
<td>40-60</td>
<td>0</td>
<td>40-50</td>
<td>5-40</td>
<td>5-15</td>
</tr>
<tr>
<td>Other Calendered Types**</td>
<td>40-97</td>
<td>0-30</td>
<td>0-50</td>
<td>2-30</td>
<td>0-7</td>
</tr>
</tbody>
</table>

* Note that this Table should not be directly used for MQA or CQA Documents, since neither the Agency nor the Authors of the Report intend to provide prescriptive formulations for manufacturers and their respective geomembranes.

** Other geomembranes than those listed in this Table will be described in the appropriate Section.

*** CSPE geomembranes are generally fabric (scrim) reinforced.
It must be recognized that Table 3.1 and the references to it in the text to follow are meant to reflect on the current state-of-the-art. The values mentioned are not meant to be prescriptive and future research and development may result in substantial changes.

3.1.1 High Density Polyethylene (HDPE)

As noted in Table 3.1, high density polyethylene (HDPE) geomembranes are made from polyethylene resin, carbon black and additives.

3.1.1.1 Resin

The polyethylene resin used for HDPE geomembranes is prepared by low pressure polymerization of ethylene as the principal monomer and having the characteristics listed in ASTM D-1248. As seen in Fig. 3.1, the resin is usually supplied to the manufacturer or formulator in an opaque pellet form.

![Polyethylene Pellets](image)

Figure 3.1 - HDPE Resin Pellets

Regarding the preparation of a specification or MQA document for the resin component of an HDPE geomembrane, the following items should be considered:

1. The polyethylene resin, which is covered in ASTM D-1248, is to be made from virgin, uncontaminated ingredients.

2. The quality control tests performed on the incoming resin will typically be density (either ASTM D-792 or D1505) and melt flow index which is ASTM D-1238.
3. Typical natural densities of the various resins used are between 0.934 and 0.940 g/cc. Note that according to ASTM D-1248 this is Type II polyethylene and is classified as medium density polyethylene.

4. Typical melt flow index values are between 0.1 and 1.0 g/10 min as per ASTM D-1238, Cond. 190/2.16.

5. Other tests which can be considered for quality control of the resin are melt flow ratio (comparing high-to-low weight melt flow values), notched constant tensile load test as per ASTM D-5397, and a single point notched constant load test, see Hsuan and Koerner (1992) for details. The latter tests would require a plaque to be made from the resin from which test specimens are taken. The single point notched constant load test is then performed at 30% yield strength and the test specimens are currently recommended not to fail within 200 hours.

6. Additional quality control certification procedures by the manufacturer (if any) should be implemented and followed.

7. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

8. An HDPE geomembrane formulation should consist of at least 97% of polyethylene resin. As seen in Table 3.1 the balance is carbon black and additives. No fillers, extenders, or other materials should be mixed into the formulation.

9. It should be noted that by adding carbon black and additives to the resin, the density of the final formulation is generally 0.941 to 0.954 g/cc. Since this numeric value is now in the high density polyethylene category according to ASTM D-1248, geomembranes of this type are commonly referred to as high density polyethylene (HDPE).

10. Regrind or rework chips (which have been previously processed by the same manufacturer but never used as a geomembrane, or other) are often added to the extruder during processing. This topic will be discussed in section 3.2.2.

11. Reclaimed material (which is polymer material that has seen previous service life and is recycled) should never be allowed in the formulation in any quantity. This topic will be discussed in section 3.2.2.

3.1.1.2 Carbon Black

Carbon black is added into an HDPE geomembrane formulation for general stabilization purposes, particularly for ultraviolet light stabilization. It is sometimes added in a powder form at the geomembrane manufacturing facility during processing, or (generally) it is added as a preformulated concentrate in pellet form. The latter is the usual case. Figure 3.2 shows photographs of carbon black powder and of concentrate pellets consisting of approximately 25% carbon black in a polyethylene resin carrier.

Regarding the preparation of a specification or MQA document for the carbon black component of HDPE geomembranes, the following items should be considered.

1. The carbon black used in HDPE geomembranes should be a Group 3 category, or lower, as defined in ASTM D-1765.
Figure 3.2 - Carbon Black in Particulate Form (Upper Photograph) and as a Concentrate (Lower Photograph)
2. Typical amounts of carbon black are from 2.0% to 3.0% by weight per ASTM D-1603. Values less than 2.0% do not appear to give adequate long-term ultraviolet protection; values greater than 3.0% begin to adversely effect physical and mechanical properties.

3. Current carbon black dispersion requirements in the final HDPE geomembrane are usually required to be A-1, A-2 or B-1 according to ASTM D-2663. Sample preparation is via ASTM D-3015. It should be noted, however, that this test method is directed at polymeric materials containing relatively large amounts of carbon black, e.g., thermostet elastomers with carbon black contents of approximately 18% by volume. ASTM D-35 Committee on Geosynthetics has a Task Group formulating a new standard focused at carbon black dispersion for formulations containing less than 5% carbon black. Thus this standard will be applicable for the 2 to 3% carbon black currently used in polyethylene formulations.

4. In the event that the carbon black is mixed into the formulation in the form of a concentrate rather than a powder, the carrier resin of the concentrate should be the same generic type as the base polyethylene resin.

3.1.1.3 Additives

Additives are introduced into an HDPE geomembrane formulation for the purposes of oxidation prevention, long-term durability and as a lubricant and/or processing aid during manufacturing. It is quite difficult to write a specification for HDPE geomembranes around a particular additive, or group of additives, because they are generally proprietary. Furthermore, there is research and development ongoing in this area and thus additives are subject to change over time.

If additives are included in a specification or MQA document, the description must be very general as to the type and amount. However, the amount can probably be bracketed as to an upper value.

1. The nature of the additive package used in the HDPE compound may be requested of the manufacturer.

2. The maximum amount of additives in a particular formulation should not exceed 1.0% by weight.

3.1.2 Very Low Density Polyethylene (VLDPE)

As seen in Table 3.1, very low density polyethylene (VLDPE) geomembranes are made from polyethylene resin, carbon black and additives. It should be noted that there are similarities between VLDPE and certain types of linear low density polyethylene (LLDPE). The linear structure and lack of long-chain branching in both LLDPE and VLDPE arise from their similar polymerization mechanisms although the catalyst technology is different. In the low-pressure polymerization of LLDPE, the random incorporation of alpha olefin comonomers produces sufficient short-chain branching to yield densities in the range of 0.915 to 0.930 g/cc. The even lower densities of VLDPE resins (from 0.890 to 0.912 g/cc) are achieved by adding more comonomer (which produces more short-chain branching than occurs in LLDPE, and thus a lower level of crystallinity) and using proprietary catalysts and reactor technology. Since VLDPE is more commonly used than LLDPE for geomembranes in waste containment applications, this section is written around VLDPE. It can be used for LLDPE if the density is at the low end of the above mentioned range. The situation is under discussion by many groups as of the writing of this
3.1.2.1 Resin

The polyethylene resin used for VLDPE geomembranes is a linear polymer of ethylene with other alpha-olefins. As with HDPE, the resin is generally supplied to the manufacturer in the form of pellets, recall Fig. 3.1.

Some specification or MQA document items for VLDPE resins follow:

1. The very low density polyethylene resin is to be made from completely virgin materials. The natural density of the resin is less than 0.912 g/cc, however, a unique category is not yet designated by ASTM.

2. A VLDPE geomembrane formulation should consist of approximately 94-96% polymer resin. As seen in Table 3.1, the balance is carbon black and additives.

3. Typical quality control tests for VLDPE resin will be density, via ASTM D-792 or D1505, and melt flow index via ASTM D-1238.

4. Additional quality control certification procedures of the manufacturer (if any) should be implemented and followed.

5. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

6. Regrind or rework chips (which have been previously processed by the same manufacturer but never used as a geomembrane, or other) are often added to the formulation during processing. This topic will be discussed in section 3.2.2.

7. Reclaimed material (which is polymer that has seen previous service life and is recycled) should never be allowed in any quantity. This topic will be discussed in section 3.2.2.

3.1.2.2 Carbon Black

Carbon black is added to VLDPE geomembrane formulations for general stabilization purposes, particularly for ultraviolet light stabilization. It is added either in a powder form at the geomembrane manufacturing facility, or it is added as a preformulated concentrate in pellet form, recall Fig. 3.2.

Some items to be included in a specification or MQA document follow:

1. The carbon black used in VLDPE geomembranes should be a Group 3 category, or lower, as defined in ASTM D-1765.

2. Typical amounts of carbon black are from 2.0% to 3.0% by weight as per ASTM D-1603. Values less than 2.0% do not appear to give adequate long-term ultraviolet protection, while values greater than 3.0% begin to negatively effect physical and mechanical properties.

3. Current carbon black dispersion requirements in the final HDPE geomembrane are usually required to be A-1, A-2 or B-1 according to ASTM D-2663(8). Sample
preparation is via ASTM D-3015. It should be noted, however, that this test method was directed at polymeric materials containing relatively large amounts of carbon black, e.g., thermoset elastomers with carbon black contents of approximately 18% by volume. ASTM D-35 Committee on Geosynthetics has a Task Group formulating a new standard focused at carbon black dispersion for formulations containing less than 5% carbon black which is the amount used in formulation of VLDPE geomembranes.

4. In the event that the carbon black is mixed into the formulation in the form of a concentrate rather than a powder, the carrier resin of the concentrate should be identified.

3.1.2.3 Additives

Additives are introduced into a VLDPE formulation for the purposes of anti-oxidation, long-term durability and as a lubricant and/or processing aid during manufacturing. It is quite difficult to write a specification for VLDPE geomembranes around a particular additive, or group of additives, because they are generally proprietary. Furthermore, there is research and development ongoing in this area and thus additives are subject to change over time.

If additives were included in a specification or MQA document, the description must be very general as to the type and amount. However, the amount can probably be bracketed as to an upper value.

1. The nature of the additive package used in the VLDPE compound may be requested of the manufacturer.

2. The maximum amount of additives in a particular formulation should not exceed 2.0% for smooth sheet or 4.0% for textured sheet by weight.

3.1.3 Other Extruded Geomembranes

Recently, there have been developed other variations of extruded geomembranes. Four have seen commercialization and will be briefly mentioned.

One variation is a coextruded light colored surface layer onto a black base layer for the purpose of reduced surface temperatures when the geomembrane is exposed for a long period of time. The usual application for this material is as a liner for surface impoundments which have no soil covering or sacrificial sheet covering. In the formulation of the light colored surface layer the carbon black is replaced by a pigment (often metal oxides, such as titanium dioxide) which acts as an ultraviolet screening agent. This results in a white, or other light colored surface. The coextruded surface layer is usually relatively thin, e.g., 5 to 10 percent of the total geomembrane’s thickness.

A second coextrusion variation is HDPE/VLDPE/HDPE sheet where the two surface layers of HDPE are relatively thin with respect to the VLDPE core. Thickness percentages of 20/60/20 are sometimes used. The interface of these coextruded layers cannot be visually distinguished since the polymers merge into one another while they are in the molten state, i.e., such geomembranes are not laminated together after processing, but are coextruded during processing.

A third variation of coextrusion is to add a foaming agent, such as nitrogen gas, into the surface layer extruder(s). This foaming agent expands and bursts at the surface of the sheet as it cools. The resulting surface is very rough and is generally referred to as textured. This variation will be described in Sections 3.2.3.4 and 3.2.4.4 for HDPE and VLDPE, respectively.
A fourth variation of extruded geomembranes is a generic polymer group under the classification of fully crosslinked elastomeric alloys (FCEA). This group of polymers is described in ASTM D-5046. The particular geomembrane type that has been used in waste containment applications is a thermoplastic elastomeric alloy of polypropylene (PP) and ethylene-propylene diene monomer (EPDM). The EPDM is fully crosslinked and suspended in a PP matrix in a process called dynamic vulcanization. The mixed polymer is extruded in a manner similar to the geomembrane types discussed in this section.

3.1.4 Polyvinyl Chloride (PVC)

As seen in Table 3.1, polyvinyl chloride (PVC) geomembranes are made from polyvinyl chloride resin, plasticizer(s), fillers and additives.

3.1.4.1 Resin

The polyvinyl chloride resin used for PVC geomembranes is made by cracking ethylene dichloride into a vinyl chloride monomer. It is then polymerized to make PVC resin. The PVC resin (in the form of a white powder) is then compounded with other components to form a PVC compound.

In the preparation of a specification or MQA document, the following items concerning the PVC resin should be considered.

1. The polyvinyl chloride resin should be made from completely virgin materials.

2. A PVC compound will generally consist of 50-70% PVC resin, by weight.

3. Typical quality control tests on the resin powder will be contamination, relative viscosity, resin gels, color and dry time. The specific test procedures will be specified by the manufacturer. Often they are other than ASTM tests.

4. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

5. Quality control certification procedures used by the manufacturer should be implemented and followed.

3.1.4.2 Plasticizer

Plasticizers are added to PVC formulations to impart flexibility, improve handling and modify physical and mechanical properties. When blended with the PVC resin the plasticizer(s) must be completely mixed into the resin. Since the resin is a powder, and the plasticizers are liquid, mixing of the two components continues until the liquid is completely absorbed by the powder. The result is usually a powder which can be readily conveyed. However, it is also possible to wet blend with acceptable results. There are two general categories of possible plasticizers; monomeric plasticizers and polymeric plasticizers. There are many specific types within each category. For example, monomeric plasticizers are sometimes phthalates, epoxides and phosphates, while polymeric plasticizers are sometimes polyesters, ethylene copolymers and nitrile rubber.

For a specification or MQA document written around PVC plasticizer(s), the following items should be considered.
1. If more than one type of plasticizer is used in a PVC formulation they must be compatible with one another.

2. The plasticizer(s) in a PVC compound are generally from 25-35% of the total compound by weight.

3. The exact type of plasticizer(s) used by the manufacturers are rarely identified. This is industry-wide practice and due to the long history of PVC is generally considered to be acceptable.

4. The plasticizer(s) should be certified by the manufacturer as having a successful past performance or as having been used on a specific number of projects.

3.1.4.3 Filler

The filler used in a PVC formulation is a relatively small component (recall Table 3.1), and (if used at all) is generally not identified. Calcium carbonate, in powder form, has been used but other options also exist. Certification as to successful past performance could be requested.

3.1.4.4 Additives

Other additives for the purpose of ease of manufacturing, coloring and stabilization are also added to the formulation. They are generally not identified. Certification as to successful past performance may be requested.

3.1.5 Chlorosulfonated Polyethylene (CSPE-R)

As seen in Table 3.1, chlorosulfonated polyethylene (CSPE) geomembranes consist of chlorosulfonated polyethylene resin, fillers, carbon black (or colorants) and additives. The finished geomembrane is usually fabricated with a fabric reinforcement, called a “scrim”, between the individual plys of the material. It is then designated as CSPE-R.

3.1.5.1 Resin

There are two different types of chlorosulfonated polyethylene resin used to make CSPE geomembranes. One is a completely amorphous polymer while the other is a thermoplastic material containing a controlled amount of crystallinity to provide useful physical properties in the uncured state while maintaining flexibility without the need of any plasticizers. The second type is generally used to manufacture geomembranes. CSPE is made directly from branched polyethylene by adding chlorine and sulfur dioxide. The chlorosulfonic groups act as preferred cross-linking sites during the polymer aging process. In the typical commercial polymer there is one chlorosulfonyl group for each 200 backbone carbon atoms.

CSPE resin pieces usually arrive at the sheet manufacturing facility in large cartons. They are somewhat pillow shaped (about 1 cm diameter) and 2 cm in length. The resin pieces (see Fig. 3.3) are relatively spongy in their resistance to finger pressure. Alternatively, CSPE can be premixed with carbon black in slab form which is then referred to as a master batch. The master batch is usually made by a formulator and shipped to the manufacturing facility in a prepared form.
In preparation of a specification or MQA document, the following items concerning the CSPE resin should be considered.

1. The CSPE resin should be made from completely virgin materials.

2. The formulation will usually be based on 40 to 60% of resin, by weight.

3. Typical MQC tests on the CSPE resin will be Mooney viscosity, chlorine content, sulfur content and a series of vulcanization properties (e.g., rheometry and high temperature behavior).

4. The CSPE resin can be premixed with carbon black in slab form (referred to as a “master batch”) and shipped to the manufacturers facility.

5. Additional quality control certification procedures used by the manufacturer should be implemented and followed.

6. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.
3.1.5.2 Carbon Black

The amount of carbon black in CSPE geomembranes varies from 5 to 36%. The carbon black functions as an ultraviolet light blocking agent, as a filler and aids in processing. The usual types of carbon black used in CSPE formulations are N 630, N 774, N 762 and N 990 as per ASTM D-1765. When low percentages of carbon black are used N 110 to N 220 should be used. When the carbon black is premixed with the resin and produced in the form of a master batch of pellets, it is fed directly into the mixer with the other components, such as fillers, stabilizers and processing aids.

A specification on carbon black in CSPE geomembranes, could be framed around the type and amount of carbon black as just described, but this is rarely the case. Typical MQC certification procedures should be available and implemented.

3.1.5.3 Fillers

The purposes of blending fillers into the CSPE compound are to provide workability and processability. The common types of fillers are clay and calcium carbonate. Both are added in powder form and in quantities ranging from 40 to 50%.

Specifications are rarely written around this aspect of the material, however MQC certification procedures should be available and implemented.

3.1.5.4 Additives

Additives are used in CSPE compounds for the purpose of stabilization which is used to distinguish the various grades. The industrial grade of CSPE geomembranes uses lead oxide as a stabilizer, whereas the potable water grade uses magnesium oxide or magnesium hydroxide. These stabilizers function as acid acceptors during the polymer aging process. During aging, hydrogen chloride or sulfur dioxide releases from the polymer and the metal oxides react with these substances inducing cross linking over time.

Specifications are rarely written around the type and quantity of additives used in CSPE, however MQC certification procedures should be written around each additive, be available and be implemented.

3.1.5.5 Reinforcing Scrim

CSPE geomembranes are usually fabricated with a reinforcing “scrim” between two plys of polymer sheets. This results in a three-ply laminated geomembrane consisting of geomembrane, scrim, geomembrane which is sealed together, under pressure, to form a unitized system. The geomembrane is said to be reinforced and then carries the designation CSPE-R. Other options of multiple plys are also available. The scrim imparts dimensional stability to the material which is important during storage, placement and seaming. It also imparts a major increase in mechanical properties over the unreinforced type, particularly in the tensile strength, modulus of elasticity and tear resistance of the final geomembrane.

The reinforcing scrim for CSPE geomembranes is a woven fabric made from polyester yarns in a standard “basket” weave. Note that there are usually many fine fibers (of very fine diameter) per individual yarn, e.g., 100 to 200 fibers per yarn depending on the desired strength. The yarns, or “strands” as they are referenced in the industry, are spaced close enough to one another to achieve the desired properties, but far apart enough to allow open space between them.
so that the opposing geomembrane sheet surfaces can adhere together. This is sometimes referred to as “strike-through” and is measured by a ply-adhesion test. The designation of reinforcing scrim is based on the number of yarns, or strands, per inch of woven fabric. The general range is from 6 x 6 to 20 x 20, with 10 x 10 being the most common. A 10 x 10 scrim refers to 10 strands per inch in the machine (or warp) direction and an equal number of 10 strands per inch in the cross machine (or weft) direction.

It must also be mentioned that the polyester scrim yarns must be coated for them to have good bonding to the upper and lower CSPE sheets. Various coatings, including latex, polyvinyl chloride and others, have been used. The exact formulation of the coating material (or “ply enhancer”) is usually proprietary.

Regarding a specification or MQA document for the fabric scrim in CSPE-R geomembranes the following applies.

1. The type of polymer used for the scrim is usually specified as polyester, although nylon has been used in the past. It should be identified accordingly.
2. The strength of the fabric scrim can be specified and, when done, is best accomplished in tensile strength units of pounds per individual yarn rather than individual fiber strength.
3. The strike-through is indirectly quantified in specifications on the basis of ply adhesion requirements. This will be discussed later.

3.1.6 Other Calendered Geomembranes

Within the category of calendered geomembranes there are other types that have not been described thus far. They will be briefly noted here along with similarities and/or differences to those just described.

Chlorinated polyethylene (CPE) has been used as a polymer resin in the past for either non-reinforced or scrim reinforced geomembranes. Its production and ingredients are similar to CSPE, or CSPE-R, with the obvious exception of the nature of the resin itself. In contrast to CSPE, CPE contains no sulfur in its formulation.

Ethylene interpolymer alloy (EIA) is always used as a reinforced geomembrane, thus EIA-R is its proper designation. The resin is a blend of ethylene vinyl acetate and polyvinyl chloride resulting in a thermoplastic elastomer. The fabric reinforcement is a tightly woven polyester which requires the polymer to be individually spread coated on both sides of the fabric. Note, however, that there are other related products being developed under different trademarks in this general category.

Among the newer geomembranes is polypropylene (PP) which is a very flexible olefinic polymer based on new polypropylene resin technology. This polymer has been converted into sheet by calendering, with and without scrim reinforcement, and by flat die and blown film extrusion processes. Factory fabrication of large panels is possible. The initial field trials of this type of geomembrane are currently ongoing.

3.2 Manufacturing

Once the specific type of geomembrane formulation that is specified has been thoroughly
mixed it is then manufactured into a continuous sheet. The two major processes used for manufacturing of the various types of sheets of geomembranes are variations of either extrusion (e.g., for HDPE, VLDPE, and LLDPE) or calendering (e.g., for PVC, CSPE and PP). Spread coating (the least used process) will be briefly mentioned in section 3.2.8.

3.2.1 Blending, Compounding, Mixing and/or Masticating

Blending, compounding, mixing and/or masticating of the various components described in Section 3.1 is conventionally done on a weight percentage basis. However, each geomembrane’s processing is somewhat unique in its equipment and procedures. Even for a particular type of geomembrane, manufacturers will use different procedures, e.g., batch methods versus continuous feed systems, for blending or mixing.

Nevertheless, a few general considerations are important to follow in the preparation of a specification or MQA document.

1. The blending, compounding, mixing and/or masticating equipment must be clean and completely purged from previously mixed materials of a different formulation. This might require sending a complete cycle of purging material through the system, sometimes referred to as a “blank”.

2. The various components of the formulation are added on a weight percentage basis to an accuracy set by industry standards. Different components are often added to the mixture at different locations in the processing, i.e., the entire batch is not necessarily added at the outset.

3. By the time the complete formulation is ready for extrusion or calendering it must be completely homogenized. No traces of segregation, agglomeration, streaking or discoloration should be visually apparent in the finished product.

3.2.2 Regrind, Reworked or Trim Reprocessed Material

“Regrind”, “reworked” or “trim” are all terms which can be defined as finished geomembrane sheet material which has been cut from edges or ends of rolls, or is off-specification from a surface blemish, thickness or other property point of view. Figure 3.4(a) shows a photograph of HDPE regrind chips. VLDPE chips appear similar to HDPE. Figure 3.4(b) shows a photograph of PVC edge strips i.e., edge of sheet material cut off to meet specific roll width requirements. Excess edge trimmings of PVC sheet is fed back into the production system. CSPE-R trim can be added similarly, however without any reinforcing scrim.

These materials are reintroduced during the blending, compounding and/or mixing stage in controlled amounts as a matter of cost efficiency on the part of the manufacturer. Note that regrind, rework and trim material must be clearly distinguished from “recycled”, or “reclaimed”, material which is finished sheet material that has actually seen some type of service performance and has subsequently been returned to the manufacturing facility for reuse into new sheet material.

In preparing a specification or MQA document on the use of reprocessed material, the following items should be considered:

1. Regrind, reworked or trim materials in the form of chips or edge strips may be added if the material is from the same manufacturer and is exactly the same formulation as the geomembrane being produced.
Figure 3.4(a) - HDPE Regrind Chips

Figure 3.4(b) - PVC Edge Strips

Figure 3.4 - Photographs of Materials to be Reprocessed
2. Generally HDPE and VLDPE will be added in chip form as “regrind” in controlled amounts into the hopper of the extruder.

3. Generally PVC, CSPE and PP will be added in the form of a continuous strip of edge trimmings into the roll mill which precedes calendering. For scrim reinforced geomembranes it is important that the edge trim does not contain any portion of the fabric scrim.

4. The maximum amount of regrind, reworked or trim material to be added is a topic of considerable debate. Its occurrence in the completed sheet is extremely difficult, if not impossible, to identify much less to quantify by current chemical fingerprinting methods. Thus its maximum amount is not suggested in this manual. It should be mentioned that if regrind is not permitted to be used, the manufacturer may charge a premium over current practice.

5. It is generally accepted that no amount of “recycled”, or “reclaimed” sheet material (in any form whatsoever) should be added to the formulation.

3.2.3 High Density Polyethylene (HDPE)

High density polyethylene (HDPE) geomembranes are manufactured by taking the mixed components described earlier and feeding them into a hopper which leads to a horizontal extruder, see Fig. 3.5. In the manufacturing of HDPE geomembranes many extruders are 200 mm (8.0 inch) diameter systems which are quite large, e.g., up to 9 m (30 ft. long). In an extruder, the components enter a feed hopper and are transported via a continuous screw through a feed section, compression stage, metering stage, filtering screen and are then pressure fed into a die. The die options currently used for HDPE geomembrane production are either flat horizontal dies or circular vertical dies, the latter production technique often being referred to as “blown film” extrusion. The length of flat dies and the circumference of circular dies determine the width of the finished sheet and vary greatly from manufacturer to manufacturer. Some detail is given below.

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![Figure 3.5 - Cross-Section Diagram of a Horizontal Single-Screw Extruder for Polyethylene](image-url)

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3.2.3.1 Flat Die - Wide Sheet

A conventional HDPE geomembrane sheet extruder can feed enough polymer to produce sheet up to approximately 4.5 m (15 ft.) wide in typical HDPE thicknesses of 0.75 to 3.0 mm (30 to 120 mils), see Fig. 3.6. Recently, one manufacturer has used two such extruders in parallel to produce sheet approximately 9.0 m (30 ft.) wide.

Figure 3.6 - Photograph of a Polyethylene Geomembrane Exiting from a Relatively Narrow Flat Horizontal Die

Insofar as a specification or MQA document for finished HDPE geomembranes made by flat die extrusion, the following items should be considered.

1. The finished geomembrane sheet must be free from pinholes, surface blemishes, scratches or other defects (e.g., nonuniform color, streaking, roughness, carbon black agglomerates, visually discernible regrind, etc.).

2. The nominal and minimum thicknesses of the sheet should be specified. The minimum value is usually related to the nominal thickness as a percentage. Values range from 5% to 10% less than nominal.
3. The maximum thickness of the sheet is rarely, if ever, specified. This is for the obvious reason that if a manufacturer wishes to supply sheet thicker than specified it is generally acceptable. It is also done, however, to allow for those manufacturers with unique variations of flat die extrusion (such as horizontal ribs or factory fabricated seams) to not be excluded from the market.

4. The finished sheet width should be controlled to be within a set tolerance. This is usually done by creating a sheet larger than called for, and trimming the edges immediately before final rolling onto the wind-up core. (The edge trim is subsequently ground into chips and used as regrind as previously described). Flat die extrusion of HDPE sheet should meet a $\pm 2.0\%$ width specification.

5. Other MQC tests such as strength, puncture, tear, etc. should be part of a certification program which should be available and implemented.

6. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

7. The trimmed and finished sheet is wound onto a hollow wind-up core which is usually heavy cardboard or (sometimes) plastic pipe. The outside diameter of the core should be at least 150 mm (6.0 in). It obviously must be stable enough to support the roll without buckling or otherwise failing during handling, storage and transportation.

8. Partial rolls for site specific project details may be cut and prepared for shipment per the contract drawings.

3.2.3.2 Flat Die - Factory Seamed

Since there are commercial extruders which produce sheets less than 6 m (20 ft) wide, the resulting sheet widths can be factory seamed into wider panels before shipment to the field. All of the specification details just described apply to narrow sheets as well as to wide sheets.

The method of factory seaming should be left to the discretion of the manufacturer. The factory seams, however, must meet the same specifications as the field seams (to be described later).

3.2.3.3 Blown Film

By using a vertically oriented circular die the extruder can feed molten polymer in an upward orientation creating a large cylinder of polyethylene sheet, see Fig. 3.7. Since the cylinder of polymer is closed at the top where it passes over a set of nip rollers which advances the cylinder, air is generally blown within it to maintain its dimensional stability. Note that upward moving air is also outside of the cylinder to further aid in stability. After passing through the nip rollers, the collapsed cylinder is cut longitudinally, opened to its full width, brought down to floor level and rolled onto a wind-up core. Note that collapsing the cylinder and passing it through the nip rollers results in two creases. After slitting the collapsed cylinder and opening it to full width, remnants of the two creases remain.
Figure 3.7 (a) - Photograph of Blown Film Manufacturing of Polyethylene Geomembranes

Fig. 3.7(b) - Sketch of Blown Film Manufacturing of Polyethylene Geomembranes
Regarding a specification or MQA document for blown film produced HDPE geomembranes, the following applies:

1. The finished geomembrane sheet shall be free from pinholes, surface blemishes, scratches or other defects (e.g., nonuniform color, streaking, roughness, carbon black agglomerates, visually discernible regrind, etc.). Note that two machine direction creases from nip rollers are automatically induced into the finished sheet at the 1/4 distances from each edge.

2. The nominal and minimum thickness of the sheet should be specified. The minimum value is usually related to the nominal thickness as a percentage. Values referenced range from 5% to 10% less than nominal.

3. The maximum thickness of the sheet is rarely, if ever, specified. This is for the obvious reason that if a manufacturer wishes to supply sheet thicker than specified it is generally acceptable.

4. The finished sheet width should be controlled to be within a set tolerance. HDPE geomembrane made from the blown film extrusion method should meet a ±2.0% width specification.

5. Other MQC tests such as tensile strength, puncture, tear, etc., should be part of a certification program which should be available and implemented.

6. The finished sheet is wound onto a hollow wind-up core which is usually heavy cardboard or sometimes plastic pipe. The outside diameter of the core should be at least 150 mm (6.0 in.). It must be stable enough to support the roll without buckling or otherwise failing during handling, storage and transportation.

7. It is important that the two creases located at the 1/4-points from the edges of the sheet are wound on the core such that they will face upward when deployed in the field. The reason for this is so that scratches will not occur on the creases if the sheets are shifted on the soil subgrade when in an open and flat position.

8. Partial rolls for site specific project details may be cut and prepared for shipment as per the contract drawings.

3.2.3.4 Textured Sheet

By creating a roughened surface on a smooth HDPE sheet, a process called “texturing” in this document, a high friction surface can be created. There are currently three methods used to texturize smooth HDPE geomembranes: coextrusion, impingement and lamination, see Fig. 3.8.

The coextrusion method utilizes a blowing agent in the molten extrudate and delivers it from a small extruder immediately adjacent to the main extruder. When both sides of the sheet are to be textured, two small extruders (one internal and one external to the main extruder) are necessary. As the extrudate from these smaller extruders meets the cool air the blowing agent expands, opens to the atmosphere and creates the textured surface(s).
Figure 3.8 - Various Methods Currently Used to Create Textured Surfaces on HDPE Geomembranes
**Impingement** of hot HDPE particles against the finished HDPE sheet is a second method of texturing. In this case, hot particles are actually projected onto the previously prepared sheet on one or both of its surfaces in a secondary operation. The adhesion of the hot particles to the cold surface(s) should be as great, or greater, than the shear strength of the adjacent soil or other abutting material. The lengthwise edges of the sheets can be left non-textured for up to 300 mm (12 in.) so that thickness measurements and field seaming can be readily accomplished.

The third method for texturizing HDPE sheet is by *lamination* of an HDPE foam on the previously manufactured smooth sheet in a secondary operation. In this method a foaming agent contained within molten HDPE provides a froth which produces a rough textured laminate adhered to the previously prepared smooth sheet. The degree of adhesion is important with respect to the shear strength of the adjacent soil or other abutting material. If texturing on both sides of the geomembrane is necessary, the roll must go through another cycle but now on its opposite side. The lengthwise edges of the sheets can be left non-textured for up to 300 mm (12 in.) so that thickness measurements and field seaming can be readily accomplished.

Regarding the writing of a specification or MQA document on textured HDPE geomembranes the following points should be considered.

1. The surface texturing material should be of the same type of polymer and formulation as the base sheet polymer and its formulation. If other chemicals are added to the texturing material they must be identified in case of subsequent seaming difficulties.

2. The degree of texturing should be sufficient to develop the amount of friction as needed per the manufacturers specification and/or the project specifications.

3. The quality control of the texturing process can be assessed for uniformity using an inclined plane test method, e.g., GRI GS-7*.

4. The actual friction angle for design purposes should come from a large scale direct shear test simulating site specific conditions as closely as possible, e.g., ASTM D-5321.

5. The thickness of the base geomembrane should be micrometer measured (according to ASTM D-751) along the smooth edge strips of textured geomembranes made by impingement or lamination. For those textured geomembranes with no smooth edge strips, i.e., for blown film coextruded materials, an overall average thickness can be estimated on the basis of the roll weight divided by total area with suitable incorporation of the density of the material. Alternatively, a tapered point micrometer for measuring screw threads has also been used for point-to-point measurements.

6. Other MQC tests such as tensile strength, puncture, tear, etc., should be part of a certification program which should be available and implemented.

7. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

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* The Geosynthetic Research Institute (GRI) provides interim test methods for a variety of geosynthetic related topics until such time as consensus organizations (like ASTM) adopt a standard on the same topic. At that time the GRI standard is abandoned.
3.2.4 Very Low Density Polyethylene (VLDPE)

Very low density polyethylene (VLDPE) geomembranes are manufactured by taking the mixed components described earlier and feeding them into a hopper which leads to a horizontal extruder, recall Fig. 3.5. In the extruder, the blended components enter via a feed hopper and are transported via a continuous screw, through a feed section, compression stage, metering stage, filtering screen and are then pressure fed into a die. The die options currently used for VLDPE geomembrane production are either flat horizontal dies or circular vertical dies, the latter often being referred to as “blown film” extrusion. The width of flat dies and the circumference of circular dies vary greatly from manufacturer to manufacturer. The techniques are the same as were described in the manufacture of HDPE geomembranes.

3.2.4.1 Flat Die - Wide Sheet

A conventional VLDPE sheet extruder can feed enough polymer to produce sheet up to approximately 4.5 m (15 ft.) wide in typical VLDPE thicknesses of 0.75 to 3.0 mm (30 to 120 mils), recall Fig. 3.6. In developing a specification or MQA document for the manufacture of VLDPE geomembranes the following should be considered:

1. The finished geomembrane sheet must be free from pinholes, surface blemishes, scratches or other defects (e.g., carbon black agglomerates, visually discernible regrind, etc.).

2. The minimum thickness of the sheet should be specified. It is usually related to the nominal thickness as a percentage. Values range from 5% to 10% less than nominal.

3. The maximum thickness of the sheet is rarely, if ever, specified. This is for the obvious reason that if a manufacturer wishes to supply sheet thicker than specified it is generally acceptable. It is also done, however, to allow for those manufacturers with unique variations of flat die extrusion (such as horizontal ribs or factory fabricated seams) to not be excluded from the market.

4. The finished sheet width should be controlled to be within a set tolerance. This is usually done by creating a sheet larger than called for, and trimming the edges immediately before final rolling onto the wind-up core. (The edge trim is subsequently ground into chips and used as regrind as previously described). Flat die extrusion of VLDPE sheet can readily meet a ± 0.25% width specification.

5. Other MQC tests such as tensile strength, puncture, tear, etc. should be part of a certification program which should be available and implemented.

6. The trimmed and finished sheet is wound onto a hollow wind-up core which is usually heavy cardboard or sometimes plastic pipe. The outside diameter of the core should be at least 150 mm (6.0 in). It obviously must be stable enough to support the roll without buckling or otherwise failing.

7. Partial rolls for site specific project details may be cut and prepared for shipment as per contract drawings.

3.2.4.2 Flat Die - Factory Seamed

Since there are commercial extruders which produce significantly narrower sheet than just
discussed, the resulting narrow sheet widths can be factory seamed into wider panels before shipment to the field. All of the specification details just described apply to narrow sheets as well as to wide sheets.

The method of factory seaming should be left to the discretion of the manufacturer. The factory seams, however, must be held to the same destructive and nondestructive testing procedures as with field seams (to be described later).

3.2.4.3 Blown Film

By using a circular die oriented vertically the extruder can feed molten polymer in an upward orientation creating a large cylinder of polymer, recall Fig. 3.7. Since the cylinder is closed at the top where it passes over a set of nip rollers which advances the cylinder, air is generally contained within it maintaining its dimensional stability. Note that upward moving air is also outside of the cylinder to further aid in stability. After passing beyond the nip rollers the cylinder is cut longitudinally, opened to its full width, brought down to floor level and rolled onto a stable core.

The following items should be considered in preparing a specification or MQA document for blown film VLDPE geomembranes.

1. The finished geomembrane sheet shall be free from pinholes, surface blemishes, scratches or other defects (carbon black agglomerates, visually discernible regrind, etc.). Note that two machine direction creases from nip rollers are automatically induced into the finished sheet at the 1/4 distances from each edge.

2. The minimum thickness of the sheet should be specified. It is usually related to the nominal thickness as a percentage. Values referenced range from 5% to 10% less than nominal.

3. The maximum thickness of the sheet is rarely, if ever, specified. This is for the obvious reason that if a manufacturer wishes to supply sheet thicker than specified it is generally acceptable.

4. The finished sheet width should be controlled to be within a set tolerance. VLDPE geomembrane made from the blown film extrusion method should meet a ±2.0% width specification.

5. Other MQC tests such as tensile strength, puncture, tear, etc. should be part of a certification program which should be available and implemented.

6. The finished sheet is wound onto a hollow wind-up core which is usually heavy cardboard or sometimes plastic pipe. The outside diameter of the core should be at least 150 mm (6.0 in.). It obviously must be stable enough to support the roll without buckling or otherwise failing.

7. Partial rolls for site specific project details may be cut and prepared for shipment as per contract drawings.

3.2.4.4 Textured Sheet

By creating a roughened surface on a smooth VLDPE sheet, a process called “texturing” in
this document, a high friction surface can be created. There are currently three methods used to texturize smooth VLDPE geomembranes: coextrusion, impingement and lamination, recall Fig. 3.8.

The coextrusion method utilizes a blowing agent in the molten extrudate and delivers it from a small extruder immediately adjacent to the main extruder. When both sides of the sheet are to be textured, two small extruders, one internal and one external to the main extruder, are necessary. As the extrudate from these smaller extruders meets the cool air the blowing agent expands, opens to the atmosphere and creates the textured surface(s).

Impingement of hot polyethylene particles against the finished VLDPE sheet is a second method of texturing. In this case, hot particles are actually projected onto the previously prepared sheet on one or both of its surfaces in a secondary operation. The adhesion of the hot particles to the cold surface(s) should be as great, or greater, than the shear strength of the adjacent soil or other abutting material. The lengthwise edges of the sheets can be left non-textured for up to 30 cm (12 in.) so that thickness measurements and field seaming can be readily accomplished.

The third method for texturizing VLDPE sheet is by lamination of a hot polyethylene foam on the previously manufactured smooth sheet in a secondary operation. In this method a foaming agent contained in molten polyethylene provides a froth which produces a rough textured laminate adhered to the previously prepared smooth sheet. The degree of adhesion is important with respect to the shear strength of the adjacent soil or other abutting material. If texturing of both sides of the geomembrane is necessary the roll must go through another cycle but now on its opposite side. The lengthwise edges of the sheets can be left non-textured for up to 300 mm (12 in.) so that thickness measurements and field seaming can be readily accomplished.

Regarding the writing of a specification or MQA document on textured VLDPE geomembranes the following points should be considered.

1. The surface texturing material should be polyethylene of density equal to the VLDPE, or greater. The latter is often the case. If other chemicals are added to the texturing material they must be identified in case of subsequent seaming difficulties.

2. The degree of texturing should be sufficient to develop the amount of friction as needed per the manufacturers specification and/or the project specifications.

3. The quality control of the texturing process can be assessed for uniformity using an inclined plane test method, e.g., GRI GS-7.

4. The actual friction angle for design purposes should come from a large scale direct shear test simulating site specific conditions as closely as possible, e.g., ASTM D-5321.

5. The thickness of the base geomembrane should be micrometer measured (according to ASTM D-751) along the smooth edge strips of textured geomembranes made by impingement or lamination. For those textured VLDPE geomembranes with no smooth edge strips, i.e., for blown film coextruded materials, an overall average thickness can be estimated on the basis of the roll weight divided by total area with suitable incorporation of the density of the material. Alternatively, a tapered point micrometer for measuring screw threads has also been used for point-to-point measurements. Care must be exercised, however, because VLDPE thickness measurements with a point micrometer are very sensitive to pressure.
6. Other MQC tests such as tensile strength, puncture, tear, etc., should be part of a certification program which should be available and implemented.

7. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

3.2.5 Coextrusion Processes

As mentioned previously in Section 3.1.3, there are other variations of manufacturing polyethylene geomembranes. The basic manufacturing principle of adding the desired components to an extruder and having the molten polymer exit a flat horizontal die or a circular vertical die is always the same. What is different between these variations and the single component HDPE or VLDPE just described is the coextrusion process along with the idiosyncrasies of the particular materials utilized.

In coextrusion, two or three extruders simultaneously introduce molten polymer into the same die. As the different materials exit the die and are cooled they commingle with one another such that local blending and molecular entanglement occur and no discrete separation layer exists. Thus coextrusion is fundamentally different from the lamination of different surfaces together or of preformed sheets together under heat and pressure. Different variations of coextrusion of polyethylene geomembranes are described as follows.

Since polyethylene resin is supplied as a opaque pellet, the addition of colorants (rather than carbon black) can produce white, blue, green, etc., colored geomembranes. The benefit for geomembranes having these light colors is to reduce the surface temperature of the geomembrane when it is required to be exposed, e.g., as liners for surface impoundments or floating covers for reservoirs. Figure 3.9 shows how the temperature differences between white and black can be very significant. The white (or light) colors generally utilize titanium dioxide (or other metal oxides) in amounts not exceeding 1.0% by weight. Note that only a thin surface layer (approximately 10-20% of the total thickness) is treated in this manner. The balance of the geomembrane contains carbon black and is treated in the same manner as described previously.

Figure 3.9 - Geomembrane Surface Temperature Differences Between Black and White Colors

A second variation of polyethylene is to coextrude a “sandwich” of HDPE on each side of VLDPE in the center. The purpose of such a combination is to provide high chemical resistance on the top and bottom of the sheet (via the HDPE) and to have high flexibility and out-of-plane
elongation properties within the core (via the VLDPE). The thickness percentages of these components are approximately 20%, 60% and 20% of the total thickness of the sheet, respectively.

Third, it is possible to coextrude a surface layer to conventional HDPE or VLDPE which contains a gas that expands when cooled. Thus the molten polymer moves through the die in a regular manner only to have the expanding gas rapidly exit on its surface(s). This forms a roughened, or textured, surface which depends on the amount of gas and thickness of the coextruded surface layer. Similar extruders can be used on both sides of the parent sheet. The purpose of such texturing is to increase the interface friction between the textured geomembrane and the material above and/or below it, refer to Sections 3.2.3.4 and 3.2.4.4.

Lastly, it is possible to coextrude other polymers than polyethylene. As noted in Section 3.1.3, fully crosslinked elastomeric alloys (FCEA) can be extruded or could be coextruded with other polymers.

3.2.6 Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) geomembranes are manufactured by taking proportional weight amounts of PVC resin (a dry powder) and plasticizer (a liquid) and premixing them until the plasticizer is absorbed into the resin. Filler (in the form of a dry powder) and other additives (also usually dry powders) are then added to the plasticized resin and the total formulation is mixed in a blender. Various types of high intensity or low intensity blenders can be used. Note that PVC rework in the form of chips, rather than edge trim, can be introduced at this point.

The resulting free-flowing powder compound is fed into a mixer which has heat introduced thereby initiating a reaction between the various components. These mixers can be either batch type (e.g., Banbury) or continuous types (e.g., Farrel), see Figs. 3.10(a) and (b), respectively. In these mixers, the temperature is approximately 180°C (350°F) which melts the mixture into a viscous mass. The mixed material is then removed from the discharge door or port onto a conveyor belt. From the conveyor belt the viscous material is further worked (called “masticating”) in a rolling mill (or mills) into a smooth, consistent, uniform color, continuous mass of 100-150 mm (4-6 in.) in diameter. Finished product edge trim can also be introduced into the rolling mill at this point. The fully mixed formulation is then fed by conveyor directly into the sizing calender.

3.2.6.1 Calendering

PVC formulations, irrespective of the pre-processing procedures, are manufactured into continuous geomembrane sheets by a calendering process. The viscous feed of polymer coming from the rolling mill(s) is worked and flattened between counter-rotating rollers into a geomembrane sheet. Most calenders are “inverted-L” configurations, see Fig. 3.11, but other options also exist. The rollers are usually smooth surfaced (they can be slightly textured) stainless steel cylinders and are up to 200 cm (80 in.) in width. The opening distance between adjacent cylinders is set for the desired thickness of the final sheet. A rolling bank of molten material is formed between adjacent rolls. In an inverted four roll “L” calender, 3 such banks are formed. They act as reservoirs for the molten material, and help to fill the sheet to full thickness as it passes between the rolls. As the geomembrane exits from the calender, it enters an additional series of rollers for the purposes of pickoff, embossing, stripping, cooling and cutting. At least one, and perhaps two, rollers in PVC manufacturing are embossed so as to impart a surface texture on the geomembrane. The purpose of this embossing is to prevent the rolled geomembrane from sticking together, i.e., “blocking”, during wind-up, storage and transportation.
Figure 3.10 - Sketches of Various Process Mixers
In developing a specification or MQA document for the manufacturing of PVC geomembranes the following considerations are important:

1. The finished geomembrane sheet should be free from pinholes, surface blemishes, scratches or other defects (agglomerates of various additives or fillers, visually discernible rework, etc.)

2. The finished geomembrane sheet surfaces should be of a uniform color.

3. The addition of a dusting powder, such as talc, to eliminate blocking is not an acceptable practice. The powder will invariably attach to the sheet or be trapped within
the embossed irregularities and eventually be contained in the seamed area as a potential contaminant which could effect the adequacy of the seam.

4. The nominal and minimum thickness of the sheet should be specified. The minimum thickness of the finished geomembrane sheet is usually limited to the nominal thickness minus 5%.

5. The maximum thickness of the finished geomembrane sheet is generally not specified.

6. The width of the finished PVC geomembrane is dependent on the type of calender used by the manufacturer.

7. The geomembrane sheet should be edge trimmed to result in a specified width. This should be controlled to within ± 0.25%.

8. Various MQC tests such as tensile strength, puncture, tear, etc. should be part of a certification program which should be available and implemented.

9. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

10. The finished geomembrane sheet should be rolled onto stable wind-up cores of at least 75 mm (3.0 in.) in diameter.

3.2.6.2 Panel Fabrication

PVC geomembranes as just described are typically 100 to 200 cm (40 to 80 in.) wide and are transported in rolls weighing up to 6.7 kN (1500 pounds) to a panel fabrication facility, see Fig. 3.12 (upper photo). When a specific job order is placed, the rolls are unwound and placed directly on top of one another for factory seaming into a panel, see Fig. 3.12 (lower photo). A panel will typically consist of 5 to 10 rolls which are accordion seamed to one another, i.e., the left side of a particular roll is seamed to the underlying roll while the right side is seamed to the overlying roll. After seaming, the completed panel is again accordion folded (now in a lengthwise direction) and placed on a wooden pallet. It is then covered with a protective wrapper and shipped to the job site for deployment. To be noted is that some fabricators use other procedures for panel preparation.

Regarding a specification or MQA document for factory fabrication of PVC geomembrane panels, the following items should be considered.

1. The factory seaming of PVC rolls into panels should be performed by thermal or chemical seaming methods, see ASTM D-4545. It should be noted that dielectric seaming is a factory seaming method for joining PVC rolls. This is a thermal (or heat fusion) method that is acceptable and is unique to factory seaming of flexible thermoplastic geomembranes. It is currently not a field seaming method.

2. Factory seams should be subjected to the same type of destructive and nondestructive tests as field seams (to be described later).

3. When factory seams are made by chemical methods they are generally protected against blocking by covering them with a 100 mm (4 in.) wide strip of thin polyethylene film. When the panels are unfolded in the field these strips are discarded.
Figure 3.12 - Photographs of Calendered Rolls of Geomembranes After Manufacturing (Upper) and Factory Fabrication of Rolls into Large Panels for Field Deployment (Lower)
4. The finished and folded panels must be protected against accidental damage and excessive exposure during handling, transportation and storage. Usually they are protected by covering them in a heavy cardboard enclosure and placed on a wooden pallet for shipping.

5. The cardboard enclosures should be labeled and coded according to the specific job specifications.

3.2.7 Chlorosulfonated Polyethylene-Scrim Reinforced (CSPE-R)

Chlorosulfonated polyethylene geomembranes are made by mixing CSPE resin with carbon black (or their colorants) thereby making a “master batch” of these two components. Added to this master batch are fillers, additives and lubricants in a batch type mixer, e.g., a Banbury mixer, recall Fig. 3.10(a). Within the mixer the shearing action of the rotors against the ingredients generates enough heat to cause melting and subsequent chemical reactions to occur. After the mixing cycle is complete, the batch is dropped from the Banbury onto a two-roll mill, then to a conveyor leading to a second two-roll mill. In moving through the roll mill it is further mixed into a completely homogenized material having a uniform color and texture. It should be noted that edge trim is often taken from finished sheet and routed back to the roll mill for mixing and reuse.

A conveyor now transports the material directly to the calender, as shown in Fig. 3.11, and feeds it between the appropriate calender rolls.

3.2.7.1 Calendering

All CSPE formulations are manufactured into geomembrane sheets by a calendering process. Here the viscous ribbon of polymer is worked and flattened into a geomembrane sheet. Most calenders are “inverted-L” configurations, recall Fig. 3.11, but other options also exist. As the geomembrane exits the calender, it enters a series of rollers for the purposes of pickoff, stripping, cooling and cutting.

The inverted-L type calender provides an opportunity to introduce two simultaneous ribbons of the mixed and masticated polymeric compound thereby making two individual sheets of geomembranes. While this section of the manual is written around CSPE, it should be recognized that many other geomembrane types which are calendered can be made in multiple ply form as well. Since they are separately formed geomembrane sheets, they are brought together immediately upon exiting the calender to provide a laminated geomembrane consisting of two plys. Additional plys can also be added as desired, but this is not usually done in the manufacture of CSPE geomembranes.

While producing the two separate plys in an inverted-L calender as mentioned above, a woven fabric, called a reinforcing scrim, can be introduced between the two plys, see Fig. 3.13. The CSPE geomembrane is then said to be reinforced and is designed CSPE-R. It is common practice, however, to just use the acronym CSPE when referring to either the nonreinforced or reinforced variety of CSPE. The scrim is usually a woven polyester yarn with 6 x 6, 10 x 10 or 20 x 20 count. These numbers refer to the number of yarns per inch in the machine and cross machine directions, respectively. Other scrim counts are also possible.
Regarding the preparation of a specification or MQA document for multiple-ply scrim reinforced CSPE-R geomembranes the following should be considered.

1. The finished geomembrane should be free from surface blemishes, scratches and other defects (additive agglomerates, visually discernible rework, etc.).

2. The finished geomembrane sheet should be of a uniform color (which may be black, or by the addition of colorants, be white, tan, gray, blue, etc.), gloss and surface texture.

3. A uniform reinforcing scrim pattern should be reflected on both sides of the geomembrane and should be free from such anomalies as knots, gathering of yarns, delaminations or nonuniform and deformed scrim.

4. The sheet should not be embossed since the surface irregularities caused by the scrim are adequate to prohibit blocking.

5. The thickness of the sheet should be measured over the scrim and at a minimum should be the nominal thickness minus 10%.

6. The geomembrane sheet should have a salvage, i.e., geomembrane ply directly on geomembrane ply with no fabric scrim, on both edges. This salvage shall be approximately 6 mm (0.25 in.).

7. Various MQC tests such as strength, puncture, tear, ply adhesion, etc., should be part of a certification program which should be available and implemented.
8. The frequency of performing each of the preceding tests should be covered in the MQC plan and it should be implemented and followed.

9. The finished geomembrane sheet should be rolled onto stable wind-up cores of at least 75 mm (3.0 in.) in diameter.

3.2.7.2 Panel Fabrication

CSPE-R geomembranes as just described are typically 100 to 200 cm (40 to 80 in.) wide and are transported in rolls weighing up to 6.7 kN (1500 pounds) to a panel fabrication facility. When a specific job order is placed, the rolls are unwound and placed on top of one another for factory seaming into a panel, recall Fig. 3.12. A panel will typically consist of 5 to 10 rolls accordion seamed to one another. After seaming, the panel is accordion folded in its length direction and placed onto a wooden pallet. It is then appropriately covered and shipped to the job site for deployment. To be noted is that some fabricators use other procedures for panel preparation.

In preparing a specification or MQA document for CSPE-R geomembrane panels, the following items should be considered.

1. Factory seaming of CSPE-R rolls should use thermal, chemical or bodied chemical fusion methods, see ASTM D-4545. It should be noted that dielectric seaming is a factory seaming method for joining CSPE-R rolls. This is a thermal, or heat fusion, method that is acceptable and is currently unique to factory seaming of flexible thermoplastic geomembranes. It is not a field seaming method.

2. Factory seams should be subjected to the same type of nondestructive tests as field seams (to be described later). A start-up seam is made prior to making panel production seams from which destructive tests are taken (to be described later).

3. When factory seams are made by chemical fusion methods they are generally protected against sticking to the adjacent sheet (i.e., blocking) by covering them with 100 mm (4 in.) wide thin strip of polyethylene film. When the panels are unfolded in the field these strips are discarded. Other systems may not require this film.

4. The folded panels must be protected against accidental damage and excessive exposure during handling, transportation and storage. Usually they are protected by containing them in a heavy cardboard enclosure and placed on a wooden pallet for shipping.

5. The cardboard enclosures are labeled and coded according to the specific job specifications.

3.2.8 Spread Coated Geomembranes

As mentioned previously, an exception to the calendering method of producing flexible geomembranes, is the spread coating process. This process is currently unique to a geomembrane type called ethylene interpolymer alloy (EIA-R), but has been used to produce other specialty geomembranes in the past. The process utilizes a dense fabric substrate, commonly either a woven or nonwoven textile, and spreads the molten polymer on its surface. Due to the dense structure of the fabric, penetration of the viscous polymer to the opposite side is usually not complete. When
cooled, the sheet must be turned over and the process repeated on the opposite side. Adherence of
the polymer to the fabric is essential.

Geomembranes produced by the spread coating method are indeed multiple-ply reinforced
materials, but produced by a method other than calendering. MQC and MQA plans and
specifications should be framed in a similar manner as described previously for CSPE-R
geomembranes.

3.3 Handling

While there should be great concern and care focused on the manufacturers and installers of
gemembranes, it is also incumbent that they are packaged, handled, stored, transported, re-
stored, re-handled and deployed in a manner so as not to cause any damage. This section is
written with these many ancillary considerations in mind.

3.3.1 Packaging

Different types of geomembranes require different types of packaging after they are
manufactured. Generally HDPE and VLDPE are packaged around a core in roll form, while PVC
and CSPE-R are accordion folded in two directions and packaged onto pallets.

3.3.1.1 Rolls

Both HDPE and VLDPE geomembranes are manufactured and fed directly to a wind-up
core in full-width rolls. No external wrapping or covering is generally needed, nor provided.
These rolls, which weigh up to 22 kN (5000 pounds), are either moved by fork-lifts using a long
rod inserted into the core (called a “stinger”) or they are picked up by fabric slings with a crane or
hoist. Note that the slings are often dedicated to each particular roll and follow along with it until
its actual deployment. The rolls are usually stored in an outdoor area. They are stacked such that
one roll is nested into the valley of the two underlying rolls, see Fig. 3.14.

Regarding a specification or MQA document for finished rolls of HDPE geomembranes the
following applies.

1. The cores on which the rolls of geomembranes are wound should be at least 150 mm
   (6.0 in.) outside diameter.

2. The cores should have a sufficient inside diameter such that fork lift stingers can be used
   for lifting and movement.

3. The cores should be sufficiently strong that the roll can be lifted by a stinger or with
   slings without excessively deflecting, nor structurally buckling the roll.

4. The stacking of rolls at the manufacturing facility should not cause buckling of the cores
   nor flattening of the rolls. In general, the maximum stacking limit is 5 rolls high.

5. If storage at the manufacturer’s facility is for longer than 6 months, the rolls should be
   covered by a sacrificial covering, or placed within a temporary or permanent enclosure.

6. The manufacturer should identify all rolls with the manufacturer’s name, product
   identification, thickness, roller number, roll dimensions and date manufactured.