FASTENER PULL-OUT RESISTANCE OF RECYCLED POLYMER COMPOSITES

By

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FASTENER PULL-OUT RESISTANCE OF RECYCLED POLYMER COMPOSITES

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Abstract: The problem of waste plastics has created a need to find new and innovative ways to keep discarded products out of landfills and turn waste materials into new products of value. By combining carpets made from poly(ethylene terephthalate) (cPET) or polypropylene (cPP) with pellets of recycled poly(ethylene terephthalate) (rPET), recycled polyolefins (rPO), or recycled high density polyethylene (rHDPE) through compression molding recycled composite materials were made and tested to investigate their suitability for use in light structural applications. For the recycled composites to be used in many structural applications they must have the ability to be cut to measured lengths and joined together using fasteners. In this study the pull-out resistance of wood screws, bolts, and nail fasteners was tested for three recycled carpet and pellet combinations, cPET/rPET, cPP/rPO, and cPP/rHDPE. It was found that the cPP/rPO and cPP/rHDPE composites have a stronger pull-out resistance than common pine wood for all fasteners tested. The cPET/rPET composites had a stronger pull-out resistance than common pine wood for screws and bolts, but was too brittle to have a nail driven through the material without cracking. These results show great promise for recycled composite materials to find use in light structural applications and avoid taking up space in landfills.

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CHAPTER I

INTRODUCTION

In this study the fastener pull-out resistance of recycled polymer composites made using compression molding was tested. The composites were made from discarded carpet and recycled polymers pellets. The broad objective of making composites from waste carpet and recycled polymer pellets is to reduce the amount of carpet sent to landfills by extending the products' lifecycle. By turning carpet into a new composite material that can be used in light structural applications waste carpet can find new value and be diverted from taking up space in landfills and minimize its negative environmental impact.

Two types of carpets were used in this study, carpets with fibers made from poly(ethylene terephthalate) (cPET) and carpets with polypropylene (cPP) fibers. The recycled pellets used with the carpets were poly(ethylene terephthalate) (rPET), mixed polyolefins (rPO), or high-density polyethylene (rHDPE) resins. The combination of carpet and recycled polymer pellets used in this study were cPET/rPET, cPP/rPO, and cPP/rHDPE. Mixing of cPET and rPET with HDPE or PO was not pursued because preliminary results showed that PET's higher melting point caused HDPE and PO to degrade when heated to PET's melting temperature.

The ability to cut pieces of the composite materials to size and bond together using fasteners is an important characteristic of this material. To find use in light structural applications these composite materials must show that they can be securely joined together with common fasteners. The fasteners used in this study were #8 and #12 wood screws, 10-24 and 5/16-18 threaded bolts, and spiral shank, ring shank, and common nails.

The ability for the recycled composite materials to be used to construct forklift pallets for warehouse use was investigated as part of a study conducted by Oklahoma State University sponsored through the REMADE Institute and Niagara Bottling.

One of the most common materials for forklift pallet construction is pine wood [1]. Pine wood is used because of its strength to weight ratio, durability, low cost and abundance, ability to be cut and shaped into many different forms, and ability to be easily joined by fasteners, most commonly by nails and screws. For these recycled polymer composite materials to be used to construct a forklift pallet, they must match or exceed pine wood's ability to be joined together with fasteners.

Fastener pull-out resistance tests were performed on the composite materials to investigate its ability to securely hold different types of fasteners. Results were compared to pine wood as well as samples made of pure rPO, rHDPE, and rPET. Samples of carpet only cPP and cPET were also molded to obtain comparison data.

The maximum force recorded during the pull-out tests divided by the thickness of the material tested was the data used to compare each materials ability to hold fasteners against other materials. The maximum force divided by the contact area of the fastener with the material was the data used to compare each fastener's effectiveness against other fasteners.

1.1 Carpet Composition

Carpets are a common type of floor covering made of densely packed short fibers attached to a backing material. Carpets are typically manufactured and transported in large rolls and require custom installation to cover the floor of a room. Installation of carpet in homes, offices, and other buildings is done primarily for aesthetics and comfort purposes but carpet also has beneficial thermal and acoustic insulation benefits [2].

There are four layers that make up most carpets as shown in Fig. 1.1. The top face fibers make up the top layer, followed by the primary backing, the binder or adhesive, and the bottom secondary backing.

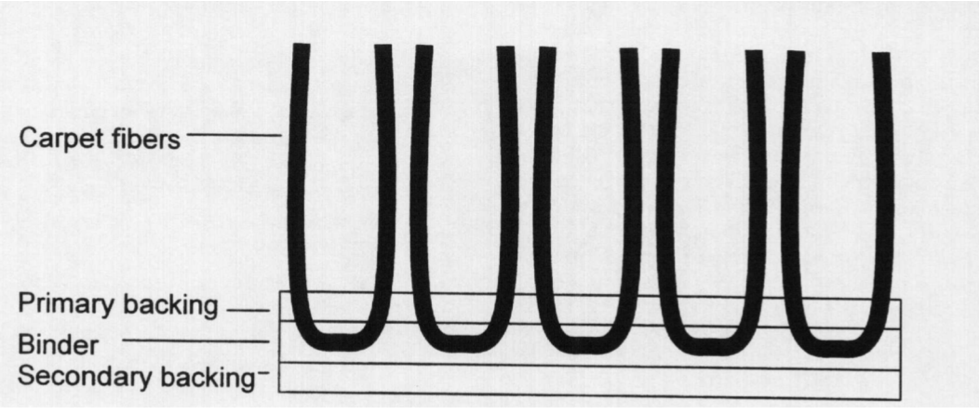

Figure 1.1: Carpet construction from [3].

Various materials such as wool, silk, and several types of polymers can be used to make carpet fibers. The primary and secondary backing materials are most commonly made from polypropylene (PP), with other less common backing materials being jute, cotton, and polyester. PP is the only material used to make both carpet fibers and backing [4]. The adhesive used to bind the secondary backing to the primary backing and secure the fibers is a carboxylated styrene butadiene rubber latex [5].

PP replaced jute as the most common material used for primary and secondary backings in the 1950s as unstable supplies of jute incentivized carpet manufactures to find an alternative solution [6]. PP is used as backing material because of its durability, inexpensive manufacturing costs, resistance to stains and shrinking, ability to form a tight weave, and manufacturing uniformity.

Woven PP carpet backings account for about 90% of all backing materials used in the manufacturing of carpet [7]. The woven backings, an example of which can be seen in Fig. 1.2, provide dimensional stability to hold and secure the tufted carpet fibers. The backings are made from polypropylene fibers woven in various densities depending on the carpet fiber gauge to be tufted through the backing. Carpet fibers are woven through the primary backing layer with the adhesive and secondary backing materials pressed onto the under part of the primary backing to secure the portion of the fiber that was woven through the primary backing in place [7]. The backing layers give the carpet its stiffness and help to keep the carpet flat on the ground and not become wrinkled from walking traffic.

Figure 1.2: Piece of carpet folded over showing fibers and backing.

Carpets can also take the form of unwoven fabrics that are formed by entangling fibers made from PET, PP, or from a wide range of other synthetic and natural materials [8]. Unwoven fabrics are formed into sheets by first evenly laying out the material on a flat surface and then chemically or mechanically bonding the fibers. Common methods used to bond the fibers together include adding resins or fusing the fibers with heat [9]. By bonding these fibrous materials sheets are formed that can cover large areas and are cheaper to manufacture per square meter than woven fabrics. Unwoven fabrics are commonly used as carpets in automobiles as they are more flexible and better at covering the contours of a car's interior [10].

Yarns that are to become the carpet face fibers are inserted through the primary backing material by a tufting machine. Tufting machines have rows of sewing needles that puncture the backing material with the yarn, which is then grabbed by a hook as the needle retracts [11]. This creates a loop of yarn sticking out of the opposite end of backing material. The length of the loops determines the carpet pile type. This process is repeated until the sheet of backing material is covered in densely packed loops. Depending on the type and style of carpet being produced, the loops are then either cut or left as is becoming one of three major carpet types; loop pile, cut pile, or mixed loop and cut pile [11].

1.2 PP Fibers

Polypropylene is a thermoplastic that has many properties that make it suitable for use as carpet fibers. PP fibers are strong and tough with the ability to recover from elongation stresses that occur with normal carpet wear [12]. PP fibers are also hydrophobic making them spill resistant and easy to clean. PP has a density of around 0.90-0.91 g/cm^3 making PP fibers one of the lightest fibers used in major industries [13]. Fibers made from PP are unaffected by most solvents at room temperature making them safe to clean with ordinary carpet cleaners. PP is also insect and microorganism resistant, aiding in its ability to keep clean [13].

The thermal conductivity of PP is affected by several factors such as degree of crystallinity but generally falls in the range of 0.11-0.22 W/mK making PP carpet a good thermal insulator [14]. PP is safe to use up to a temperature around 130° C when it starts to soften, and has a melting temperature around 165° C to 175° C, well within the range of normal room temperatures and the temperature on a hot day [15]. PP is also an electrical insulator and does not build up large static charges [13].

Manufacturing of PP is relatively cheap as fibers can be produced using continuous methods such as the extrusion process of melt-spinning [16]. Melt-spinning produces several fibers from melted polymers by forcing liquid polymer through a spinneret. The polymers are extruded at a constant rate and at a high pressure through the spinneret where the polymer strands are then cooled which causes them to solidify as they are spun together to form a yarn [17]. An example of melt spinning process can be seen illustrated in Fig. 1.3.

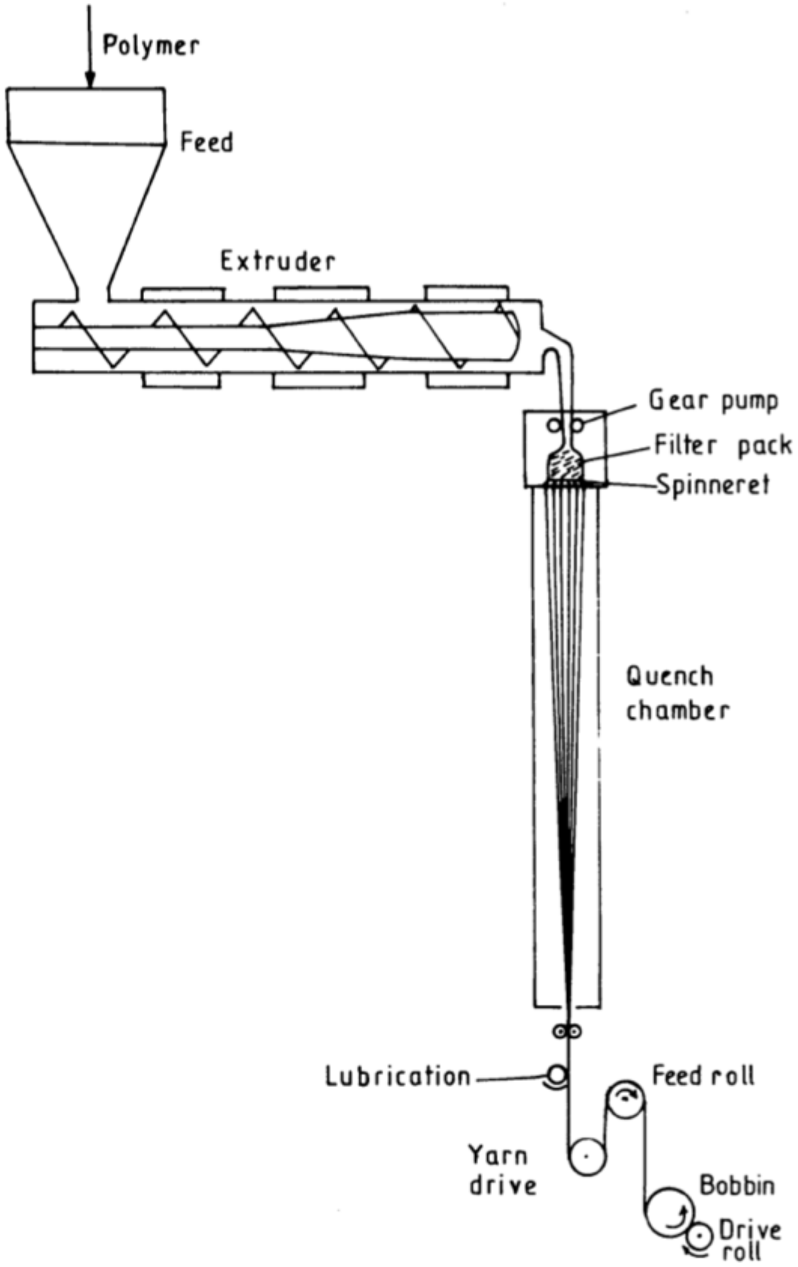

Figure 1.3: Melt spinning [16].

There are some properties of PP that make them less than ideal for carpet fibers. PP fibers are difficult to dye and have a limited color range. The color of PP is also affected by sunlight and often has pigment and light stabilizers added to improve color stability [6]. PP fibers are less resilient compared to PET and nylon fibers.

1.3 PET Fibers

The most common polymer used to make carpet fibers is nylon, but as industries have shifted to more sustainable practices, recycled PET has been gaining popularity as the polymer to use for carpet fibers. PET is a thermoplastic that is part of the polyester family of polymers [18]. It is often used in the production of food and beverage containers because of its inert properties [19]. PET is widely accepted as a safe material to use in products that contact food and beverages by health authorities because it does not leech harmful chemicals [20]. PET is also highly recyclable and because of its use in food and beverage container manufacturing, waste PET is abundant [21]. As with PP fibers, manufacturing of PET fibers is relatively inexpensive when done using melt spinning processes. Recycling waste PET to make fibers is advantageous as most PET food and beverage containers are made from high-grade PET so that even when reprocessed to make fibers, the recycled PET is still very strong and capable of making good quality fibers that can be used in the manufacturing of textiles and carpet [22].

PET fibers are suitable for carpet fibers for many reasons. The good abrasion resistance and resilience of PET fibers helps it sustain prolong wear experienced by carpet in high traffic areas. PET fibers recover from bending stresses very well and have moderate elongation recovery [23]. Another advantage of using PET fibers for carpet is that it does not require additional chemical treatments to resist stains as does nylon [22]. The density of PET is around 1.30-1.40 g/cm^3, meaning that it does not float and will sink in water. This can aid in sorting PET materials in mixed polymer waste streams by being able to use sink float separation tanks [24].

PET retains minimal amounts of moisture but not enough to increase the dye uptake of PET. Since PET is hydrophobic and does a very poor job of retaining moisture, it is difficult to dye different colors and special techniques and dye material are required. When dyed different colors, PET does not fade easily in direct sunlight. The melting temperature of PET is around 260° C, but softens at around 80° C [25]. The thermal conductivity of PET is in the range of 0.15 – 0.24 W/mK making it a good thermal insulator [26].

As the amount of recycled PET carpets being manufactured grows, so does the amount of recycled PET carpet that is being thrown out. Processes to recycle carpets with nylon fibers have been well established but because some PET carpet fibers are already made from recycled PET, recycling PET carpet is more complicated. The backing of PET carpets can be separated from the fibers and recycled in the same ways nylon carpet backings are recycled, but the fibers themselves pose a problem as they are already made from recycled PET, which is weaker and of lesser quality than virgin PET [22].

1.4 Recycling Polymers

There are four broad categories for post-consumer recycling of polymers:

1. Primary –Primary recycling is the reuse of uncontaminated scrap polymers created during manufacturing processes. Often the scrap polymers are introduced back into the same system to create products. Primary recycling is also known as re-extrusion as often most of the polymeric material that is recycled is from scrap created in extrusion manufacturing processes, or products that did meet specifications, being chopped up or pelletized and thrown back in the hopper of the extruder to be remelted. Primary recycling of post-consumer plastics can also be accomplished but is complicated as post-consumer polymer waste streams are comprised of several different polymers that must be sorted into separate polymer types. Separating out different polymer types from polymer waste sources is difficult and costly. Cleaning

must also be done to get rid of contaminants so the post-consumer polymer waste can be remelted and reused [27].

2. Secondary – Polymers are separated and reused to make products of lesser quality. Separation can be done by either chemical or mechanical processes. The separated polymers can be remelted and used again in processes to make new products such as injection or compression molding. The additional processing to separate the polymers results in a polymer blend that yields products that have less strength than products made from their virgin polymers. This is due to the remelted polymers having a lower degree of polymerization and from impurities that are present in the polymer mixture [28].
3. Tertiary – Polymer waste materials are converted into constituent molecules, often monomers, that can be used as feedstock to make new petrochemicals and polymers. The quality of the raw materials made from the feedstock is equal to that of their virgin materials. Tertiary recycling has the potential to close the loop on polymer products as the products can be turned back into their monomers and repolymerized to create polymers that have equal strength to their virgin material [29].
4. Quaternary – Energy is recovered through incinerating waste polymers. This has its own set of environmental problems as the burning polymers can create toxic gases and the ash that can be contaminated with heavy metals which can seep into waterways. With quaternary recycling polymers are burned to create heat to boil water to create steam which turns a turbine connected to a generator which creates electricity. One benefit of quaternary recycling of polymers is that the waste volume

is reduced by about 90-99%, greatly reducing the amount of space it would take up in landfills [27].

Most polymer recycling is encompassed by primary and secondary recycling processes. Tertiary recycling has become of great interest as chemical processes can completely reuse polymers and could yield products of equal quality to those of virgin materials. In addition, biological approaches are also being explored by utilizing microbes that can accelerate the degradation of polymers. These techniques are in their infancy and are yet to be proven on a significant industrial scale [30].

1.5 Recycling Carpet

Since the materials most carpets are made from are not biodegradable, a large proportion of waste carpet ends up sitting in landfills at the end of their product lifecycle [31]. To avoid sending millions of tons of carpet to landfills every year, carpets must be recycled to improve sustainability and avoid negative effects on the environment.

Pre and post-consumer carpet waste are the two broad categories of carpet recycling. Pre-consumer carpet waste are the scraps and edges of new carpet that are cut and trimmed off during packaging and installation [32]. Automobile carpets make up a large proportion of pre-consumer carpet waste because of the irregular shapes the carpets must be cut into to cover the floor of a car [33]. Overall, pre-consumer carpet waste makes up a small fraction of total carpet waste.

Post-consumer carpet waste is comprised of carpets that have been installed and used and contain contaminants such as dirt. Used carpet accounts for 1-3% of municipal waste headed to landfills. The main ways post-consumer carpets are processed to be recycled are by separating the fiber from the backing and by shredding into small pieces. By separating the fiber from the backing the polymer from the fibers can be recycled. By shredding carpet into small pieces, it can be used as an additive in concrete or as filler in other applications. It can also be melted down to create a low-quality polymer that can be used to make new products [31]. However, none of these solutions on their own have yet to make a major difference in recycling carpets

1.6 Fasteners

A fastener is a device used to rigidly join two or more objects together through mechanical force [34]. These joints can be permanent or nonpermanent depending on the type of fastener used. There are many types of fasteners but the most common are nails, screws, rivets, staples, and bolts made from steel, many of which are shown in Fig. 1.4 [34]. Fasteners can allow for the disassembly and reassembly of objects without the objects being destroyed in the process. Compared to other methods of bonding materials fasteners are quick to use and relatively inexpensive.

Figure 1.4: Variety of fasteners.

There are two major distinct types of fasteners, threaded and non-threaded. Threaded fasteners include screws and bolts which have a helical ridge which wraps around the cylindrical body of the fastener [35].

In this paper, we will refer to bolts as threaded fasteners which are used in conjunction with not only tapped nuts, but also holes that have been threaded. Traditionally, the term bolt refers to fasteners that are used to join two or more pieces of unthreaded material by being inserted through appropriately sized holes and secured using tapped nuts [35]. The head of the bolt and the nut are larger than the hole causing the material to be trapped in between. Bolts and nuts can also create a tight clamping force that holds the pieces of the material together, but can also be loose allowing the material to pivot if not secured with more bolts [35]. In this study we will use the term bolt in reference to fasteners that are threaded and used in conjunction with threaded holes or nuts.

The term screw has traditionally been used to refer to any threaded fastener that is used to secure or join two or more pieces of material where at least one material has a hole with internal threads, whether the threads are preformed or formed by the insertion of the screw [36]. In this study we will use the term screw to refer to fasteners that cut their own threads upon forced insertion in contrast to bolts which uses a hole with preformed threads or a nut.Non-threaded fasteners include nails and staples and join materials by the friction force of the materials against the shaft of the non-threaded fastener.

One disadvantage of using fasteners to join two materials together is the large amount of localized stress concentrated at each fastener hole. This is in contrast to other methods used to join materials such as welding or thermosetting adhesive bonding with polymeric materials [37]. These methods distribute the stress more evenly along the bonded joint.

1.6.1 Screws

Screws are threaded fasteners that require rotation to be driven into a material. When driven into material the thread, or helical ridge that wraps around the shaft of the screw, cuts into the material forming its own internal thread [35].

The head of a screw can take many different shapes and forms depending on the intended purpose of the screw. Drywall screws are designed to have the head of the screw sunk into the material when inserted. Other screws have large heads that protrude out of the material helping to create and distribute a clamping force on the material [38].

Screws are driven into materials by torquing the head of the fastener using a screwdriver. The drive type of a screw comes in many different shapes. The drive tip of a screwdriver is inserted into the recess shape in the screw head to rotate the fastener. Examples of drive tips that are inserted into fastener heads include phillips, flat, triple square, and torx bits, examples of which are shown in Fig. 1.5. Fastener heads can also be shaped so that they require tools that go over the head to rotate. Examples of tools that are inserted over the fastener head are sockets, nut drivers, and wrenches. Each have advantages and disadvantages such as ease of use and amount of torque that can be applied without deforming or breaking the head of the fastener [39].

Figure 1.5: Screwdriver tips and socket set.

There are many different types of screws designed to excel at holding different types of materials in different situations. The designs vary slightly but all retain raised threads that wraps around the shaft of the screw. The height of the thread, the thread pitch, and thread angle are the main variables in screw designs [40].

Drilling pilot holes for screws is often necessary to avoid cracking material. Screws often have a sharp point at the end of the shaft to aid with inserting the screw into the material or pilot hole [35].

1.6.2 Bolts

Bolts, as described in this paper, are threaded fasteners that mate with threaded holes or threaded nuts and create a clamping force. External threads are on the outside shaft of a bolt. Internal threads are on the inside of a hole or nut. A thread is the helical ridge that wraps around the inside or outside of the surface of a cylinder. The threads of the bolt must match the threads of the nut or hole it is mating with [41].

Bolt threads are generally finer than screw threads and come in different sizes. The thread pitch, angle, diameter, and height, as shown in Fig. 1.6, must all match for a bolt to fit into a threaded hole or nut. Several standard thread series for bolts have been widely adopted in industry. Unified National Coarse (UNC) and Unified National Fine (UNF) threads are the main thread series that are measured in inches. UNC and UNF threads are described by the bolt diameter and the number of threads per inch. Metric thread series are defined by the diameter of the bolt shaft and the distance between threads [42].

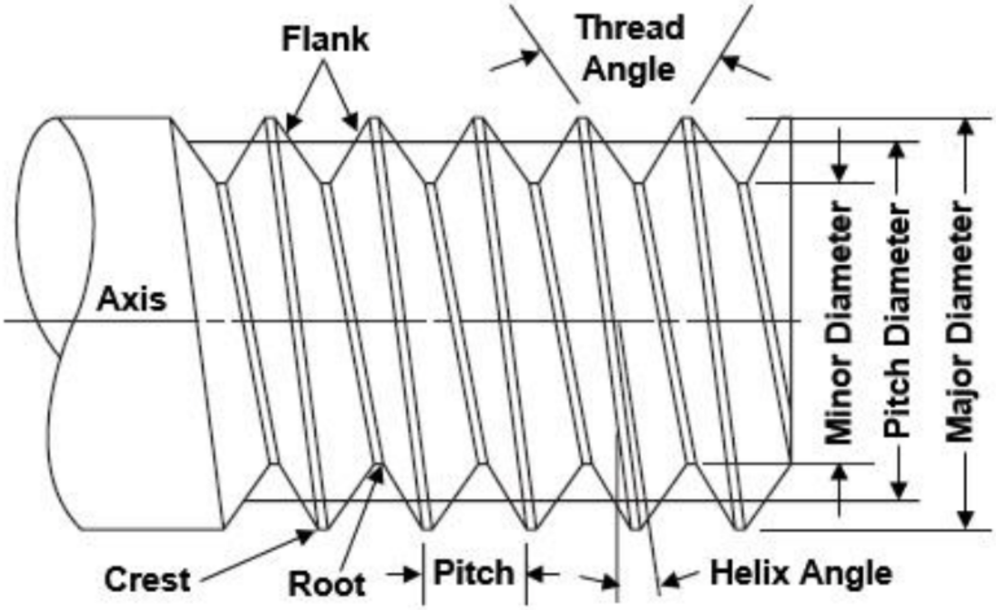

Figure 1.6: Screw thread terms [35].

As with screws, the head of the bolt can take on many different shapes. The most common head shape for bolts are hex heads which require a socket or wrench to turn. Washers are often used with nuts and bolts to distribute the clamping force over a larger area [35].

The most common tools used to cut threads are a tap and die, as shown in Fig. 1.7. A tap cuts threads on the inside of a hole and a die is used to cut threads on a rod. It is also possible to cut threads using CNC milling machines with special thread cutting end mills [43].

Figure 1.7: Tap and die for thread cutting.

1.6.3 Nails

Nails are unthreaded fasteners that when driven into a material causes the material immediately around the nail's shaft to be displaced. This displaced material grips the shaft of the nail and the friction between the material and shaft secure the nail in the material [44]. There are many kinds of nails available which are suited for different purposes. The shaft of a nail can be smooth or textured depending on the application. Nails with a spiral shank or ribbed shank are much harder to remove than smooth shank nails [45]. The head of a nail is generally flat with some nails having large heads meant to help secure the material and some having small heads meant to be driven down under the surface of the material [44].

Nails are cheaper to manufacture than threaded fasteners and can be installed faster and with more ease than threaded fasteners. This is because it often necessary to drill a pilot hole to prevent the material from cracking or to ensure precise placement of the screw. Hammers and pneumatic nail guns are the most common tools used to drive nails into material. Nail guns can drive nails into material at a rate much faster than any threaded fastener tool is able to install screws. This speed makes nails an economical option in many construction and fabrication situations [46].

1.7 Composites

Composites are a class of materials that are made of two or more different materials that have different physical and chemical properties. When combined, the different materials create a new material that is unlike the individual materials. One material in a composite acts as the reinforcement and the other the matrix [47]. The matrix binds the reinforcement material together while the reinforcement gives the material most of its strength. The interface is the region where the matrix material and reinforcement material interact. The properties of the composite are highly dependent on the behavior of the interface [48]. In some composites, the second phase is a filler rather than a reinforcement meant to take up space rather than make the material stronger.

1.8 Objective

The objective of this study was to investigate the ability of fasteners to be used with recycled composites made from post-consumer PET and PP carpets. Nylon based carpets have dominated most of the carpet market share but as manufactures have started looking to make their products more sustainable substituting PET and PP for nylon as the face fiber material has become more and attractive. Carpets made using recycled PET have been gaining more of the market share as an abundance of recycled PET is available at low cost, especially when compared to the cost of nylon processing.

Composites made from recycled materials will be of much greater use in light structural applications if they can be easily joined together using common fasteners such as screws, nails, and bolts. Finding ways to divert materials made from polymers from ending up in landfills is important to avoid the negative environmental impact these materials have at the end of their product lifecycle.

Carpet has proven to be an especially difficult material to recycle because of its complexity which makes it difficult to separate into constituent materials. Millions of tons of carpets are sent to landfills every year as incentives to recycle carpet are generally lacking. The cost to recycle carpet is high and the value of the end product is nominal as virgin plastics are cheap and readily available. Reducing the cost of recycling carpet is important for more widespread recycling of post-consumer carpet to take place. By creating a composite material that can be used in light structural applications that uses post-consumer waste carpet with minimal processing steps, we hope to create more ways for carpet to be reused. The composites materials were made by compression molding post-consumer carpet with recycled polymer pellets. The only processing done to the carpet was cutting pieces that fit snugly into the cavity of the mold. By using the carpet as a whole without the need to separate the fibers from the backing, the costs associated with recycling carpet will become much lower. In addition, the composite material created from the carpet will have value if it can be used in light structural application. We hope to incentivize the recycling of carpet and ultimately prevent millions of tons of post-consumer waste carpet from sitting in landfills by showing how compression molded recycled carpet composites can be easily made and that the properties of the recycled carpet composites make it a useful product for light structural applications.

CHAPTER II

REVIEW OF LITERATURE

Several studies have been made on the fastener pull-out resistance of materials such as wood, particle board, fiber board, polymers, plywood, oriented strandboard, and composite materials. To date, we know of no research published about the fastener pull-out resistance of compression molded materials made from carpet.

The screw and nail withdrawal resistance of several types of common woods was measured and reported in a study done by Aytekin [49]. Tests were conducted by driving nails and screws into samples then measuring how much weight or how many kilograms of force (kgf) were required to remove them. Samples dimensions were 5 cm x 5 cm x 25 cm and made from oak, stone pine, black pine, and fir lumber. A similar study reported the nail and screw withdrawal resistance strength of wood from the paulownia (*Paulownia tomentosa* Steud.) trees grown in Turkey [50].

Another study that measured the withdrawal resistance of screws from medium density fiberboard (MDF) and particleboard (PB) along with effects of pilot hole size was done by Yorur et al. [51]. The pull-out resistance of MDF and PB were also tested when soaked in water which was found to weaken the materials.

Oriented strandboard (OSB) and plywood were tested for their ability to resist having screws withdrawn from the face and edges of the materials by Erdil et al. [52]. A considerable amount of variability in the holding strength of screws was found and attributed to variables in the processing conditions used to make the OSB and plywood rather than the properties of wood itself.

The withdrawal resistance of screws from wood-plastic composites (WPC) was conducted by Haftkhani et al. in a technical report at the University of Tehran in Iran [53]. In the study, sheet metal, wood screws, and drywall screws were installed into WPC panels and withdrawal force measured. Data collected was compared to MDF and PB. It was found that screw pull-out resistance was greater for WPC than MDF and PB and that pilot hole diameter size must be optimized for maximizing pull-out resistance.

The pull-out resistance of screws in MDF reinforced with a polyurethane product was investigated by Sydor et al. [54]. The study tested 2 different screws and several different application volumes of the reinforcing agent. In the study, they found the pull-out resistance of the screws in MDF was greatly strengthened with the application of the polyurethane reinforcement into the screw hole.

Tests were done on wood flour-thermoplastic composite panels to quantify the nail and screw pull-out resistance strength and reported on by Falk et el. [55]. In the study, it was found that the screw pull-out resistance for wood flour-thermoplastic composites was equal or greater than other wood-based panels such as plywood, OBS, MDF, PB, and standard hardboard. The larger screw pull-out resistance was attributed to the ability of the thermoplastic to better transfer the load continuously around the screw thread.

At Oklahoma State University, the fastener pull-out resistance of screws in nylon and olefin carpet structural laminates fabricated using a vacuum assisted resin-infusion technique with either a vinyl ester epoxy or epoxy SC 79 was tested by Rajagopalan [56]. The study showed that the structural carpet laminates made using vacuum assisted resin transfer molding (VARTM) have good screw pull-out resistance and the ability to be joined using fasteners.

The change in pull-out resistance of screws in medium density polyethylene (PE) exposed to different conditions was investigated in a study done by Zaren and Maral [37]. They tested samples that were immersed in pure water and water saturated with NaCl at different temperatures. In their studies they found that PE immersed in pure water and NaCl saturated water had greater pull-out resistance than PE samples at ambient room conditions. This was attributed to water swelling PE and tightening its grip around the screw. In addition, they also tested the effect of thermal cycling on the pull-out resistance. Thermal cycling was done by immersing the PE samples in 100^{o} C boiling water for one minute then taking the sampled out and immediately immersing it into 0^{o} C ice water for one minute. One cycle constituted immersion in both hot and cold water. It was found that a high number of thermal cycles decreased the pull-out resistance of PE.

CHAPTER III

METHODOLOGY

The combination of carpet and recycled polymer pellets used in this study were cPET/rPET, cPP/rPO, and cPP/rHDPE. Only the methods and materials used to make the cPET/rPET, cPET only, and cPET only samples will be addressed in this section. The cPP/rPO, cPP/rHDPE, cPP only, rPO only, and rHDPE only samples were supplied by members of the research group working in a different lab. All samples were made using compression molding but the cPET/rPET shown in Fig. 3.1, cPET only, and cPET only samples were made using a different hydraulic press, heating platens, and molds than the cPP/rPO, cPP/rHDPE, cPP only, rPO only, and rHDPE only samples produced for this study.

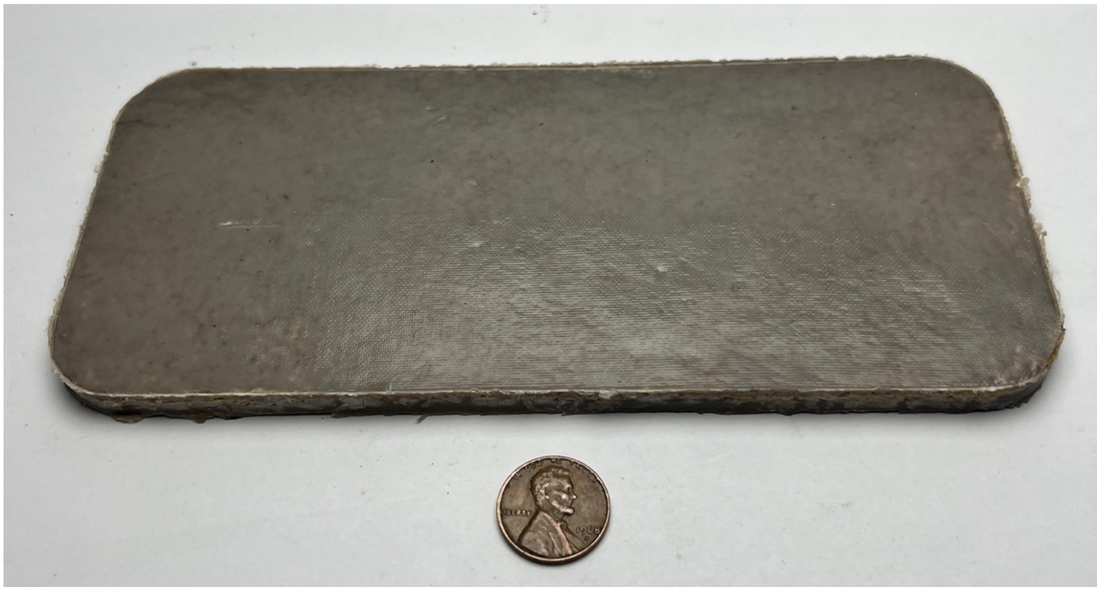

Figure 3.1: cPET/rPET 76.2 mm x 177.8 mm (3″ x 7″) sample made by compression molding

The cPET/rPET, cPET only, and cPET only samples were compression molded in three-piece aluminum molds at set time, temperature, and pressure using a programmable Carver hydraulic press with heated platens. Thin sheets of teflon (236-TFNP made by Airtech) were used to keep the composites from sticking to the top and bottom pieces of the aluminum mold.

No standards exist for testing fastener pull-out with polymer composite materials. ASTM Standard D1037-06a offers guidelines to test wood-based fiber and particle panels such as medium density fiberboard and hardboard and includes a section on pull-out testing of fasteners [57]. ASTM Standard D1761 provides basic procedures to test the withdrawal resistance of nail, staples, and screws from wood [58]. These sets of standards were used as guidance to test the fastener pull-out resistance of fasteners from the recycled carpet composite materials made as part of this study.

3.1 Molds

Two different sizes of three-piece molds were fabricated and used to make the cPET/rPET samples in this study. The smaller samples measured approximately 50.8 mm x 152.4 mm (2″x6″) and the larger samples 76.2 mm x 177.8 mm (3″x7″). Due to the limitations of fabricating the molds using a computer numerical control (CNC) milling machine, the corners of the samples have a rounded profile with a radius of approximately 9.525 mm (0.375″). The molds were machined from blocks of 6061 aluminum. The top and bottom pieces from a mold were identical and act as the plungers in the three-piece mold setup. The middle section contains the cavity that the top and bottom plungers slide into to apply pressure on the material being molded.

The molds were designed using the computer aided design (CAD) software Fusion 360. A Tormach PCNC770 CNC, shown in Fig. 3.2, milling machine upgraded with flood coolant and outfitted with appropriately sized work holding devices was used to machine the aluminum blocks into the desired shapes. Tool paths were programed using the computer aided machining (CAM) feature of the Fusion 360 software. All machining was done by the thesis author (C.S).

Figure 3.2: Tormach PCNC 770 CNC milling machine.

3.1.1 Middle Section of Mold

The walls of the middle section of the mold needed to be sufficiently thick to prevent bulging and deformation during compression molding. When the mold is under pressure the materials inside exert force on all sides of the mold. For the smaller molds making 50.8 mm x 152.4 mm (2″x6″) samples, the middle section walls were 12.7 mm (0.5″) thick. For the larger molds making the 76.2 mm x 177.8 mm (3″x7″) samples, the middle section walls were 25.4 mm (1″) thick. The height of the middle section of both sizes of molds was about 69.85 mm (2.75″).

The mold middle sections needed to be tall enough to accommodate a layer of rPET pellets sandwiched between two pieces of carpet before being compressed. The 50.8 mm x 152.4 mm (2″x6″) cavity in the middle section of the smaller molds was machined out of 101.6 mm x 177.8 mm x 69.85 mm (4″x7″x2.75″) blocks of aluminum. The cavity in the middle section of the larger molds were machined out of 127 mm x 228.6 mm x 69.85 mm (5″x9″x2.75″) blocks of aluminum. Fig. 3.3 shows the middle section of the larger mold after heavy use.

Figure 2.3: Middle section of mold.

Several different end mills were used to make the middle sections of the molds. A 38 mm (1.5″) 4 flute indexable face mill with carbide inserts was used to square all of the aluminum blocks to the desired dimensions. A high-speed steel (HSS) 19.05 mm (0.75″) diameter square end mill was used to remove most of the material from the middle section blocks, leaving only 1 mm (0.039″) of material around the inside perimeter. All speeds and feeds were set appropriately for cutting aluminum with flood coolant on the CNC mill.

A carbide 12.7 mm (0.5″) diameter torus end mill with 0.0508 mm (0.002″) radiused corners with a reach of 76.2 mm (3″) was then used to remove the remaining material from the inside perimeter. Torus end mills have a shaft that is slightly thinner than their cutting diameter and are designed for precision cutting molds that require a long reach. The thinner shaft ensures only the cutting head can contact the material. A 1 mm (0.039″) depth of cut and 0.5 mm (0.197″) stepover was used for the final passes with the torus end mill to minimize vibrations and leave a smooth surface finish.

The 12.7 mm (0.5″) diameter torus end mill necessitated that the inside corners of the middle sections of the molds be round. Theoretically the smallest inside corner radius a 12.7 mm (0.5″) diameter end mill can cut is 6.35 mm (0.25″) but doing so would result in excessive vibrations that would negatively affect the quality of the surface finish. To avoid this the radius of the inside corners was designed to be approximately 9.525 mm (0.375″) to lower the contact area of the end mill with the aluminum while cutting the inside corners of the mold middle sections. Lowering the contact area of the end mill during cutting reduces the vibrations which improves the smoothness of the cut and leaves a better surface finish. When an end mill makes a side cut and is moving parallel to the material surface only a small portion of the end mill contacts and cuts the material. However, when changing direction to cut an inside corner a larger portion of the end mill contacts the material and can cause unwanted vibration and chatter. To minimize vibrations the inside corner radius should be designed to be as large as possible.

3.1.2 Top and Bottom Section of Mold

The identical top and bottom mold pieces were comprised of 2 sections, the plunger and lip. The plunger section of the top and bottom mold pieces was designed to fit tightly into the middle section cavity to minimize liquid polymer leaking out during pressing. The plunger sections were machined to equal dimensions as their corresponding middle section cavities. To achieve a tight fit between the plungers and middle section cavities the pieces were sanded by hand and fitment frequently checked. Sanding was done until the plungers were able to slide into the middle section cavities with little resistance. The height of the top and bottom plunger sections was 34.925 mm (1.375″) or half the height of the middle section. The lip of the top and bottom pieces of the smaller mold was 12.7 mm (0.5″) thick. The lip of the top and bottom pieces of the larger mold, shown in Fig. 3.4, was 19.05 mm (0.75″) thick. The width of the lips was identical to the width of the corresponding mold middle section. An example of a completed mold is shown in Fig. 3.3.

To aid in separating the mold pieces after compression molding a sample, the length of the lip was designed to have an extra 25.4 mm (1″) hanging over two opposite edges of the middle section with a pocket machined out to fit the tip of a prybar. The overhang pockets measured about 25.4 mm x 38.1 mm x 6.35 mm (1″x1.5″x0.25″) for the larger molds and 25.4 mm x 31.75 mm x 6.35 mm (1″x1.25″x0.25″) for the smaller molds and were machined into both sides of the edges that contact the middle section of the mold. The overhang pockets were designed to protrude halfway over the mold’s middle section wall thickness to provide an area for the prybars to contact the top surface of the molds middle section.

Figure 3.4: Top/bottom section of mold.

The 38 mm (1.5″) 4 flute indexable face mill with carbide inserts was used to square all blocks of aluminum into the desired dimensions and to remove all but 1 mm (0.039″) of the material around the perimeter of the plunger. A 12.7 mm (0.5″) hi-helix square end mill with a 38.1 mm (1.5″) depth of cut was then used to make the finishing passes. The first several passes were made using a 0.25 mm (0.0098″) stepover and 5 mm (0.197″) depth of cut until only 0.25 mm (0.0098″) was left until the desired size was reached. For the last pass, a depth of cut equal to the 34.925 mm (1.375″) height of the plunger was used in combination with a slower feed rate and spindle speed of 10,000 rotations per minute (RPM). This was done to achieve an almost mirror finish cut on the outside perimeter of the plungers.

To cut the prybar overhang pockets, a 3.175 mm (1/8″) square end mill was used. All speeds and feeds were set appropriately for cutting aluminum with flood coolant.

3.1.3 Mold Finishing

After the three pieces of a mold were cut on the CNC mill, they were hand sanded using water resistant sandpaper. Multiple grits of the water resistant sandpapers were used in order from 120, 220, 320, 400, 500, 600, 1000, to 1200. Water was used to keep the sandpaper from clogging with dust and to wash away dust accumulating on the aluminum. Polishing the aluminum with the higher grit sandpapers was vital to help keep melted polymer resin from sticking to the mold pieces.

The inside of the mold's middle section was sanded first starting with the 220-grit sandpaper and working up to the 1200-grit. Sanding was done by hand with care taken to ensure that the sides of the inside cavity were sanded evenly. Once the mold's middle section was done being polished with the 1200-grit sandpaper the outer sides of the middle section of the mold were sanded and polished.

To sand the flat sides of all the mold pieces a full sheet of sandpaper was placed on a granite surface plate, shown in Fig. 3.5, and the sides of the aluminum mold rubbed on the sandpaper. The flat surface ensured even sanding starting with the 120-grit working up to 1200-grit. The sheets of sandpaper were frequently removed and rinsed with water to remove dust.

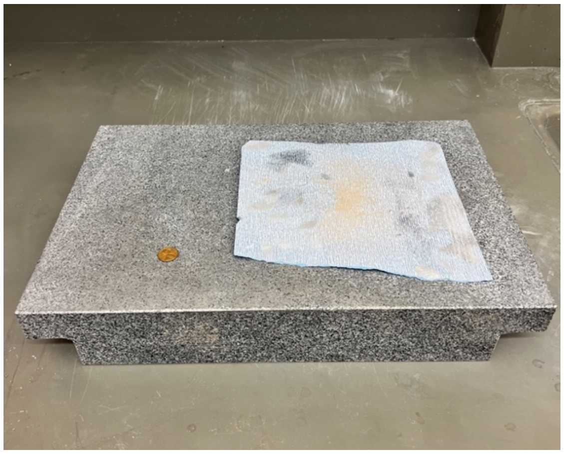

Figure 3.5: Granite surface plate.

To achieve a tight fit between the plungers and the middle section of the molds, the plungers were machined slightly oversized and were made smaller by hand sanding. The sheets of sandpaper were fixed to a rectangular metal block that was taller than the plunger height to help provide even pressure throughout the sanding process. Starting with the lowest grit, the sides of the plunger were sanded and the fitment into the mold middle section checked frequently. When the plunger was starting to fit inside the middle section of the mold the next grit of 220 sandpaper was used. The sanding process was continued with the fitment checked repeatedly. Once the plunger was able to slide all the way into the middle section, a light sanding was repeated for all grits of sandpaper. An almost air-tight fit of the 3-piece molds was achieved using this method. Fig. 3.6 shows the 3 pieces of the larger mold side by side. The molds were touched up with light sanding using high grit sandpaper when the surfaces started to dull.

Figure 3.6: 3-piece mold.

3.2 Resins

Resins used in the study are recycled PET pellets, recycled HDPE pellets, and mixed polyolefins flakes all shown in Fig 3.7. The rPET pellets were sourced from CarbonLite and made from 100% post-consumer PET beverage containers. The rHDPE pellets were sourced from KW Plastics. The PO flakes were separated out of bulk shredded mixed plastics that came from a recycling facility in California. The PO flakes were separated from the mix by pouring the shredded mixed plastics in a tank of water. The PO flakes are less dense than water and float whereas the rest of the mixed plastics would sink in water.

Prior to be being used for molding, the rPET pellets were dried in a convection oven for 6 hours at 160° to remove any moisture. PET is hygroscopic and absorbs moisture from its surroundings. To ensure maximum polymer performance from PET the pellets need to be relatively free of moisture before being used in molding [59].

Figure 3.7: rPET pellets, rHDPE pellets, and rPO flakes.

3.3 Carpet

The carpets used in this study were sourced from an Oklahoma carpet installation company that were removed from private residences before installation of new carpet. The old carpets were not cleaned and left with contaminants and uneven wear for this study.

The post-consumer carpet with PET fibers had a woven PP backing. The post-consumer carpet with PP fibers had a woven jute backing.

Rectangular samples were cut from the large segments of carpet. The inside of the middle section of the small and large molds were traced on the carpet backing using a black marker. Carpet was then cut using scissors or carpet shears.

3.4 Making Samples

For cPET/rPET samples, the amount of rPET pellets to be used was dependent on the mass of the cPET. Each sample used two pieces of cPET. A 70/30 weight ratio of cPET and rPET pellets was used to make the cPET/rPET composite samples. After the mold was loaded with the carpet and rPET pellets, the mold was placed inside the hydraulic press on the bottom heating platen and pressed using 1 MPa of pressure for a duration of about 4 minutes and 10 seconds at 270^{o} C.

Samples made from only cPET were made by loading the mold with two pieces of cPET. Samples of only rPET were made by loading 65 grams of rPET pellets into the mold. The molds were then compressed in the hydraulic press with heating platens using the same time, pressure, and heat parameters as the cPET/rPET samples.

The orientation of the carpet fibers in the mold was either with the fibers facing inward in a bottom-top-top-bottom (BTTB) configuration or backing material facing inward in top-bottom-bottom-top (TBBT) configuration as shown in Fig. 3.8. During preliminary testing it was found that a BTTB orientation of the carpet pieces was optimal for cPET/rPET. For cPP/rPO and cPP/rHDPE it was found that the TBBT orientation was optimal.

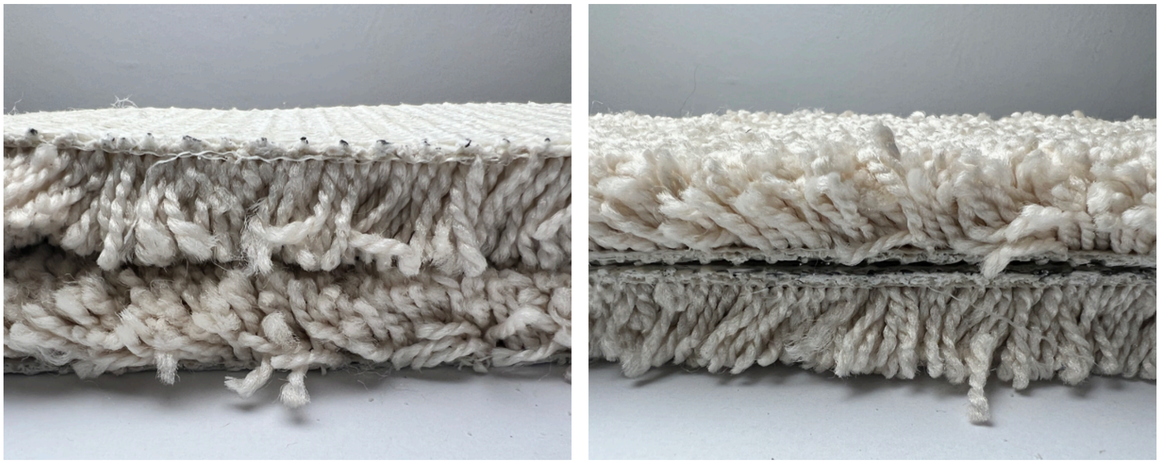

Figure 3.8: TBBT and BTTB carpet orientations for molding.

3.4.1 Loading Mold

The mold was loaded by first placing the bottom piece of the mold with the plunger facing up on a workbench and covering the top of the plunger with a sheet of the teflon film. The middle piece of the mold was then placed over the plunger covered with the teflon sheet and pushed down a few millimeters. With the middle section partially on the bottom piece, a layer of cPET was placed in the mold with fiber orientation facing downward. Then the correct mass of rPET pellets was measured and poured on top of the cPET. Then another layer of cPET was placed on top of the pellets with the fibers facing up. Another Teflon sheet would be placed over the opening of the middle section of the mold and the top plunger would then be inserted into the middle section closing the mold. Fig. 3.9 shows the steps to load the mold with cPET and rPET pellets.

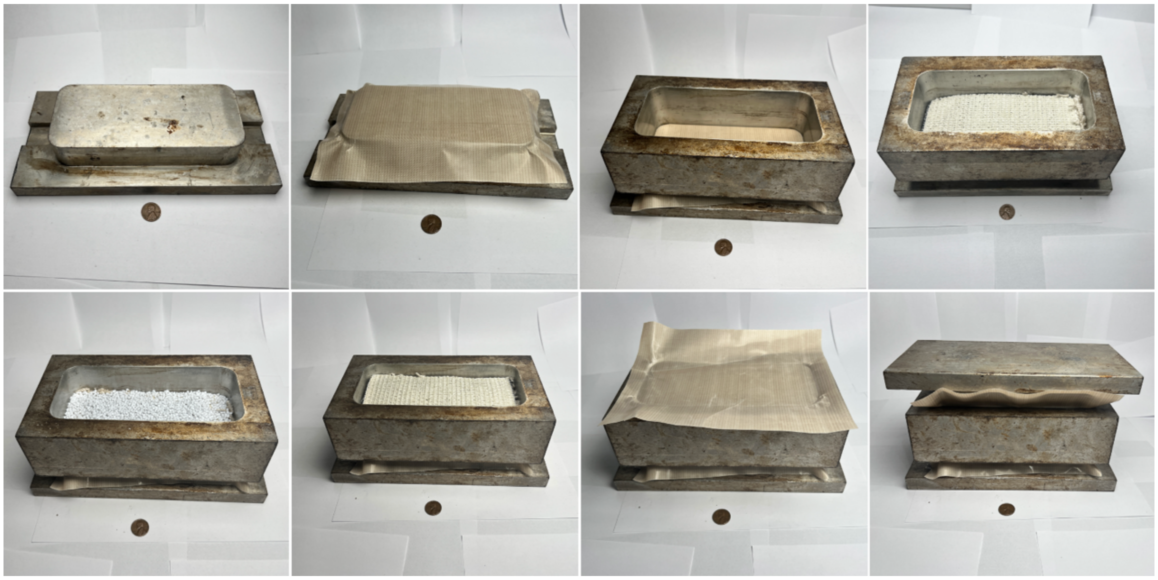

Figure 3.9: Steps to load mold.

3.4.2 Compression Molding Procedure

Before placing the mold into the Carver hydraulic lab press, shown in Fig 3.10, the platens were preheated to the desired temperature of 270° C. The hydraulic lab press was then programmed to apply 1 MPa of pressure and the loaded mold set inside on the bottom platen. To begin the test, the platens were brought together to contact the top and bottom of the mold and apply pressure, as shown in Fig 3.11. The platens compressed and heated the mold for a set length of time, then the pressure was released, and mold removed.

Figure 3.10: Carver hydraulic lab press.

Figure 3.11: Compressed mold in Carver lab press.

3.4.3 Removing Samples from Mold

The mold was removed from the hot press using high-temperature safety gloves and set on a metal workbench. The mold was clamped shut using two metal C-clamps then submerged in water until the mold reached room temperature or was cool enough to handle without gloves.

After the mold was cooled, it was opened using two prybars simultaneously to pry the top piece of the mold from the middle, as shown in Fig 3.12. The ends of the prybars were placed in the groove cut into the overhanging part of the lips and pressure exerted until the top piece separated from the middle. The mold was then flipped over, and the bottom piece removed using the same procedure. During heating and pressing melted resin would leak and solidify between the plungers and middle section in the sides of the mold making it difficult to open.

Figure 3.12: Opening mold with prybars.

After the top and bottom pieces were removed from the middle section of the mold, the sample would be left stuck in the middle cavity. The melted resin would stick to the sides of the mold making it difficult to remove the sample. The teflon sheets covered the plungers to prevent the melted PET from sticking to the top and bottom parts of the mold, but these could not be used to prevent the PET from sticking to the inside of the middle section. The sample could sometimes be freed by pressing on it by hand, but often more force was needed. A rubber mallet and pieces of wood would be used to pound the sample to try and break it free. If the melted polymer would not break free with the mallet, a boxcutter would be used to cut the PET from the aluminum sides. This would result in scratches to the inside of the mold that would periodically need to be sanded and polished.

3.5 Fastener Pull-Out

Fastener pull-out tests were conducted on the molded recycled carpet composite samples to investigate their ability to be joined with screws, bolts, and nails. The maximum force reached during fastener pull-out tests was recorded for each trial. Each material and fastener combination were tested at least 5 times.

3.5.1 Preparing Samples

Depending on which mold was used, samples ranged in size from approximately 50.8 mm x 152.4 mm (2″x6″) up to 76.2 mm x 177.8 mm (3″x7″). For the fastener pull-out tests samples were cut using a miter saw into squares measuring approximately 50.8 mm x 50.8 mm (2″x2″). Any raised material around the edges of the sample were cut or sanded off to make the samples relatively flat. Fig. 3.13 shows a sample cPET sample that has been cut to 50.8 mm x 50.8 mm (2″x2″).

Figure 3.13: 50.8 mm x 50.8 mm (2"x2") cPET sample.

The thickness of each type of sample was measured and recorded. Thicknesses would vary depending on the composition and amount of flash lost during molding and was not altered for testing.

3.5.2 Pilot Holes

Pilot holes were needed for driving the wood screws into the test materials. For each size of wood screw there is a recommended pilot hole size to drill for driving the screw into the wood. It was found that the torque required to drive a screw into the composite materials using the recommended pilot hole size for wood was up to four times higher than that of pine wood. This made it very difficult to drive in the wood screw by hand with a screwdriver. To make it easier to drive the screws in the test materials a bigger pilot hole was drilled into the materials. Through testing it was found that making the pilot hole 0.79 mm (1/32″ or 0.03″) bigger would reduce the amount of torque required to drive in a screw to about the range of torque it took to drive a screw into pine wood without a significant effect on the pull-out resistance. A cut cPET/rPET sample with pilot hole is shown in Fig 3.14

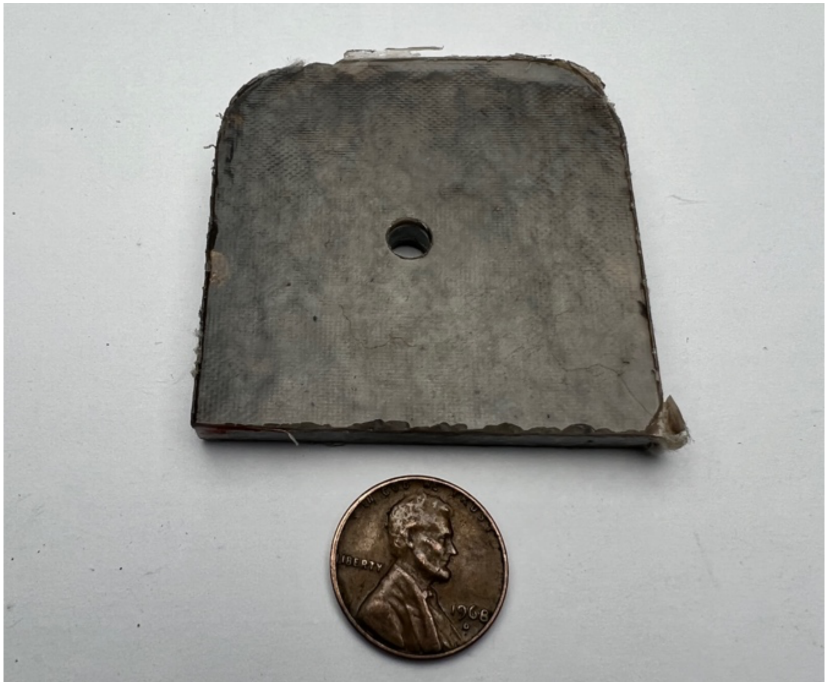

Figure 3.13: 50.8 mm x 50.8 mm (2"x2") cPET/rPET sample with pilot hole.

For #8 wood screws in pine wood, it is recommended to drill a 2.78 mm (7/64″ or 0.11″) pilot hole. For using #8 wood screws with the composite, pure resin, and carpet only samples a 3.57 mm (9/64″ or 0.14″) pilot hole was found to be optimal.

For using #12 wood screws in pine wood, it is recommended to drill a 3.57 mm (9/64″ or 0.14″) pilot hole. For using #12 wood screws with the composite materials, carpet only samples, and resin only samples a 4.37 mm (11/64″ or 0.17″) pilot hole was found to be optimal.

For cutting threads into materials using a thread cutting tap, a correctly sized hole must be drilled first. Each thread cutting tap size has a corresponding hole size that needs to be drilled.

In this study 10-24 and 5/16-18 bolts were tested. A #25 drill bit was used with the 10-24 thread cutting tap. A size F drill bit was used with the 5/16-18 thread cutting tap.

3.5.3 Fastener Pull-Out Fixture

The fastener pull-out fixture (FPOF) was custom made by C.S, to be used with an Instron universal testing machine. It was made using aluminum and steel parts bolted together. Both the top and bottom were bolted to 31.75 mm (1.25″) steel rods that slid into the base plate grips of the Intron. The steel rods had 14.22 mm (0.56″) hole machined through the round section so that they could be secured to the base plates with 12.7 mm (0.5″) steel pins that went through the base plate grips and through the steel rods. Design and toolpath generation of the FPOF was done using Fusion 360 and fabrication was done using the Tormach PCNC770 CNC milling machine.

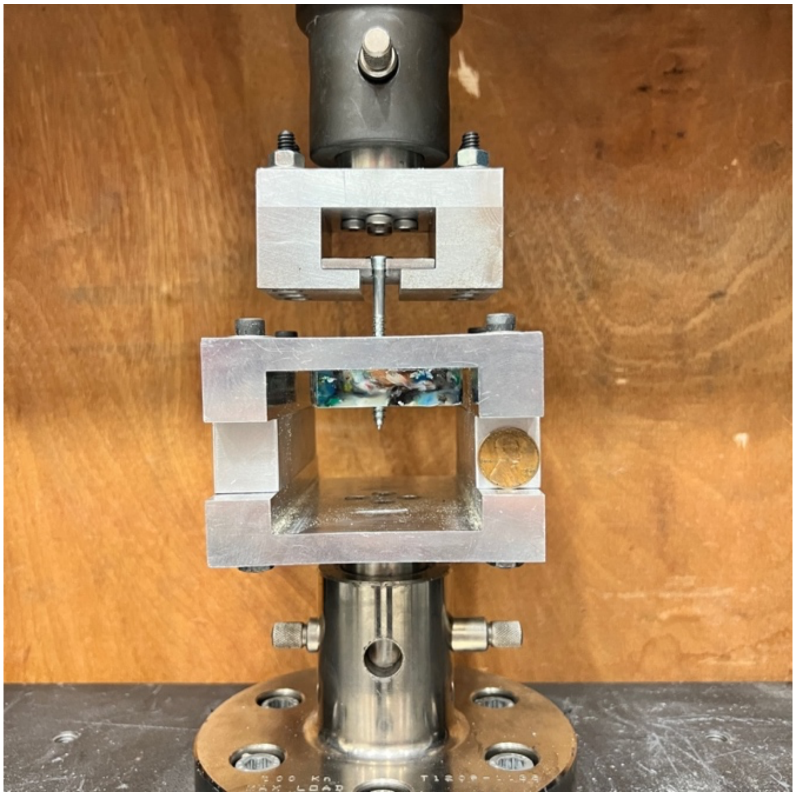

Figure 3.15: Fastener pull-out fixture (FPOF).

3.5.3.1 Head

The head of the FPOF mounted into the crossmember of the Instron and held the head of the fasteners. As shown in Fig. 3.16, several steel plates with different width slots machined halfway through the length of the plate were machined to hold the various fasteners. The slots were smaller than the head of the fastener but wider than the shaft. All the outside dimensions of the plates were the same as the plates were made to sit on the flat part of the FPOF head forks.

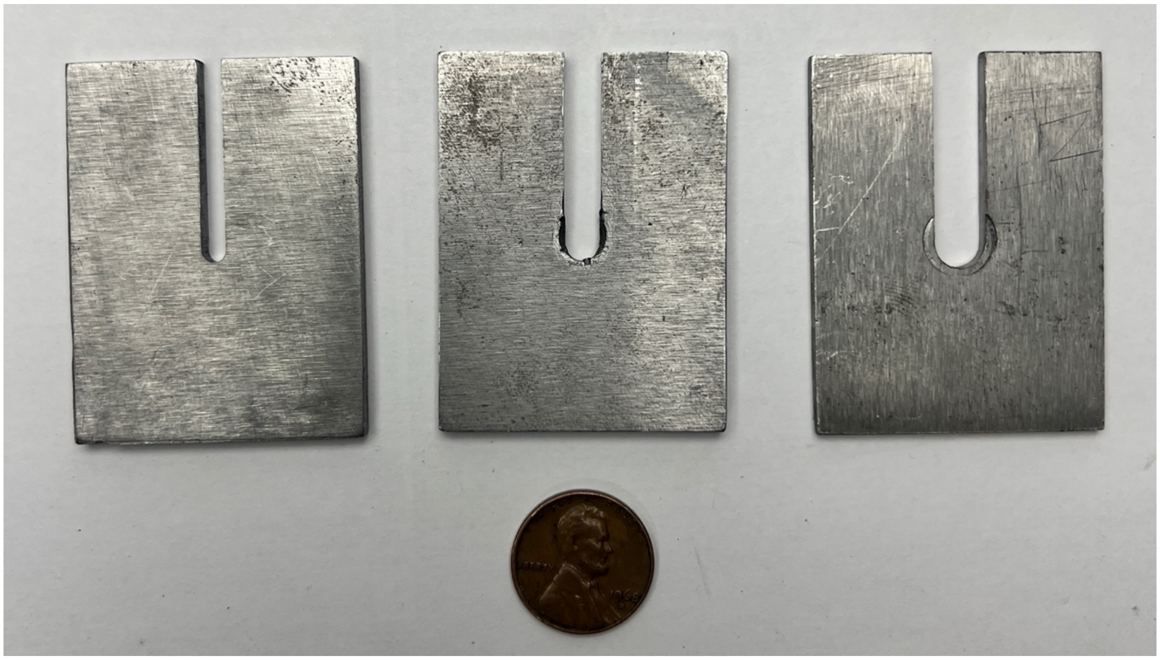

Figure 3.16: Different sizes of fastener head holding steel plates.

The forks of the FPOF head were machined from steel blocks to have an L shape to support the steel places that would hold the fastener heads. The L shaped pieces were then bolted to a steel bar which was connected to a steel rod that slid into the grip of the Instron crossmember and secured using a pin. The bolts that connect the L shaped pieces to the steel bar were counter sunk so that the bottom of the assembly could come as close as possible to the FPOF cradle. This helped minimize the length of the fasteners that were used in testing. The fasteners needed to be long enough to be driven through the material and have enough shaft length sticking out of the top of the material to reach through the hole in the top part of the cradle and through the gap between the L shaped pieces to have the head secured by the steel plate resting on the head forks. Fig. 3.17 shows the FPOF head with and without the steel holding plate.

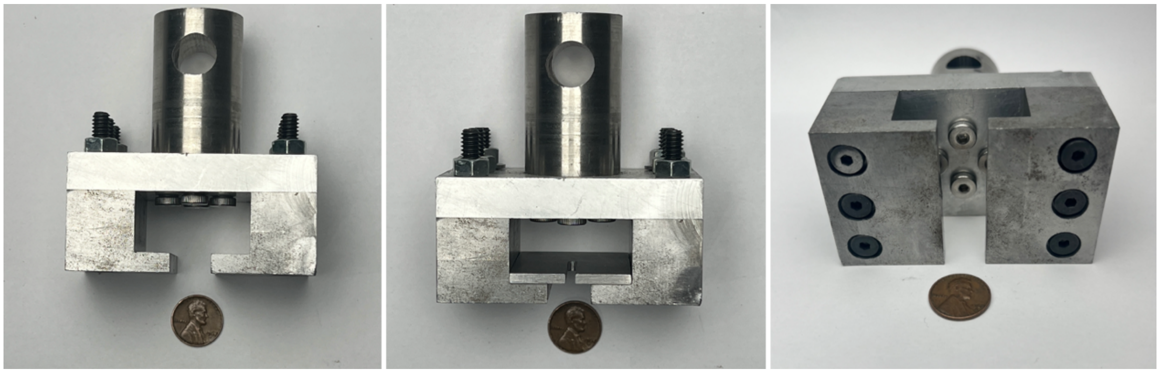

Figure 3.17: Fastener pull-out fixture (FPOF) head.

3.5.3.2 Cradle

The bottom part of the FPOF, or cradle shown in Fig. 3.18, mounts into the base of the Instron and holds the sample material with fastener. The cradle was comprised of 3 pieces. The top part with a 9.525 mm (0.375″) hole to allow the fastener to pass through, the middle spacers, and the bottom. The bottom piece was bolted to a 31.75 mm (1.25″) steel rod that was secured to the base plate grip with a 12.7 mm (0.5″) pin.

The bottom and top pieces were bolted together to allow the sample with fastener driven through to be inserted. The middle spacers were optional and allowed for thicker samples to be used. The bolts would pass through the top piece, through the middle spacers, and through the bottom and be secured using nuts and washers.

Figure 3.18: Fastener pull-out fixture (FPOF) cradle.

3.6 Fastener Pull-Out Tests

For nails and wood screws, the fasteners were driven into the samples and placed in the FPOF for testing. This required unbolting the cradle, sliding the head of the fastener through the hole in the center of the cradle's top section, then bolting the cradle pieces back together.

The bolts used in this study had heads that were too large to pass through the hole in the center of the cradle's top section. To load samples with bolts for testing, the sample with threaded holes were placed in the assembled cradle and hole aligned with the hold in the top section. Then the bottom part of the bolt was inserted into the top section's hole and threaded into the sample.

The FPOF with secured sample would then be loaded into the Instron testing machine. The crosshead with fastener head holder would be lowered and the head of the fastener secured, as shown in Fig. 3.19. The crosshead would then be raised so the sample was almost touching the top part of the FPOF cradle being careful not to apply any tension to the sample. The Intron testing machine software Bluehill Universal was used to control the Instron and log data. The Instron crosshead set to raise at a rate of 2 mm per second.

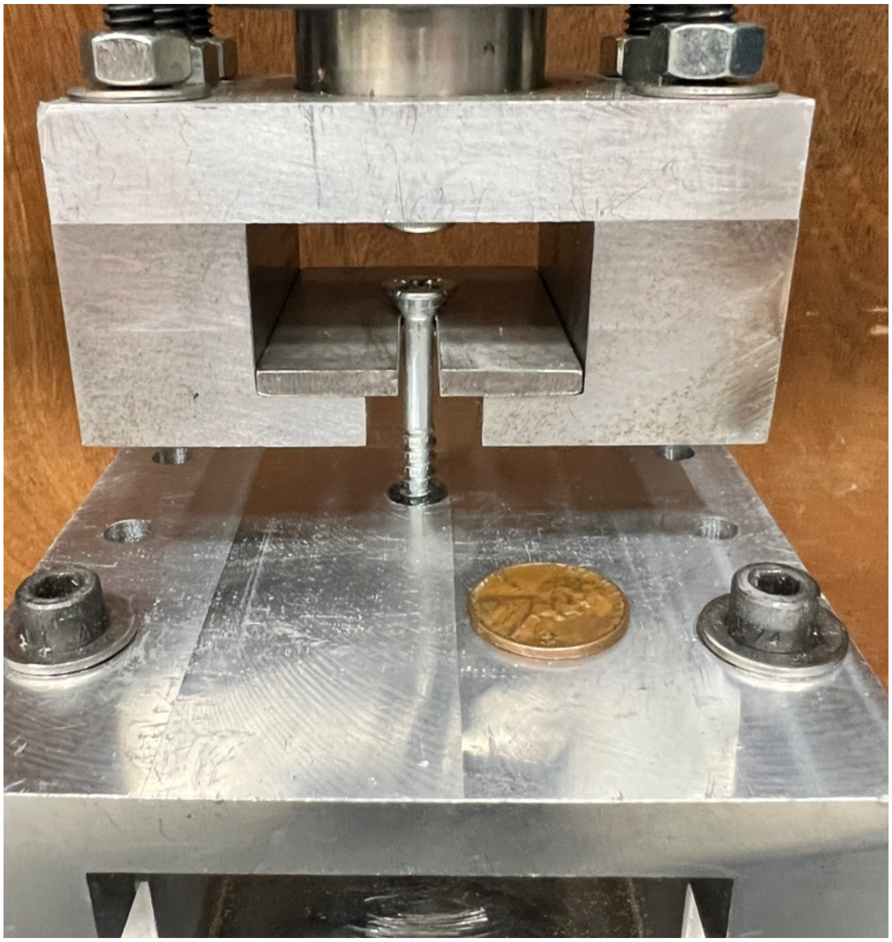

Figure 3.19: Loading fastener in FPOF.

After the FPOF was set up in the Instron the test would commence, and the fastener would be slowly pulled out of the sample as the force was measured and logged by the Bluehill program. The max force was recorded for each fastener and material combination and repeated at least 5 times. Any tests where the sample cracked and broke were thrown out and test repeated.

CHAPTER IV

FINDINGS

In this study, the maximum strength required to remove a fastener from 12 different categories of samples was tested. Fastener pull-out tests conducted on pine wood samples were used to establish a baseline to compare the data collected from the composites, pure resin, and carpet only samples. Pine wood was chosen because it is one of the most common woods used in structural applications including in the construction of forklift pallets. For the recycled carpet composite materials to find use in light structural applications the fastener pull-out resistance strengths must be equal or greater than that of pine wood.

Samples of rHDPE, rPO, and rPET only and samples of cPP and cPET only were also made and tested so that the results of carpet composite samples could be compared to the results of their individual materials.

Molding parameters for cPET/rPET composites were optimized prior to fastener pull-out testing. Parameters used for cPET/rPET molding were a 70/30 weight ratio of cPET to rPET pressed at 270^{o} C. For cPP/rPO and cPP/rHDPE composites, preliminary tests showed better properties in a range of parameters so multiple samples of the sample carpet and polymer combinations but with different molding parameters were tested.

Molding parameters that differed for cPP/rPO and cPP/rHDPE composites tested in this study were temperature and mass ratio of carpet to resin.

We expected the calculated fastener pull-out resistance values of the composite samples to fall between the values measured from the only carpet and only resin samples follow the rule of mixtures which would mean the pull-out resistances of the composite materials would fall between the pull-out resistances of their constituent carpet and resin samples.

Other than the fiber type, the two types of carpets used in this study had several differences. The carpet with PET fibers was constructed with a woven PP backing whereas the carpet with PP fibers was constructed with a woven jute backing. The length of fibers and the fiber density were also different for each carpet type.

4.1 Wood Screws

Figure 4.1: #12 and #8 wood screws.

Pilot holes were necessary for screws to be driven into the samples to prevent crackling. The amount of torque required to drive a screw into the recycled composite materials was much greater than the torque required for wood. It was found that using a drill bit 0.79 mm (1/32″ or 0.03″) larger than the drill bit recommended for the size of wood screw would not significantly affect the pull-out resistance of the composite materials while reducing the amount of torque required to drive the screw into the composites down to a level comparable to wood. For #8 wood screws a 2.78 mm (7/64″ or 0.11″) diameter drill bit is recommended for pine wood and a 3.57 mm (9/64″ or 0.14″) diameter drill bit was used for the composites. For #12 wood screws a 3.57 mm (9/64″ or 0.14″) diameter drill bit is recommended for pine wood and a 4.37 mm (11/64″ or 0.17″) diameter drill bit was used for the composites. The pine wood samples tested with wood screws retained the recommended pilot hole sizes of 2.78 mm (7/64″ or 0.11″) diameter for #8 wood screws and 3.57 mm (9/64″ or 0.14″) diameter for #12 wood screws. The diameter of the #8 wood screw shaft was 4.19 mm (0.165″). The diameter of the #12 wood screw shaft was 5.60 mm (0.22″)

Table 4.1: #8 Wood screw pull-out force/material thickness averages.

#8 Wood Screw Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	7.69	0.73	0.83
cPP/rPO 60/40 180 C	22.64	1.93	2.20
cPP/rPO 50/50 180 C	21.42	1.17	1.79
cPP/rPO 50/50 200 C	20.47	1.07	1.63
cPP/rHDPE 70/30 180 C	18.99	0.89	1.36
cPP/rHDPE 50/50 180 C	21.01	0.85	1.06
cPET/rPET	26.59	1.81	2.61
rHDPE	16.75	0.77	0.88
rPO	16.27	0.93	1.06
rPET	34.10	3.41	4.26
cPP	24.10	0.72	0.83
cPET	25.31	1.59	1.99

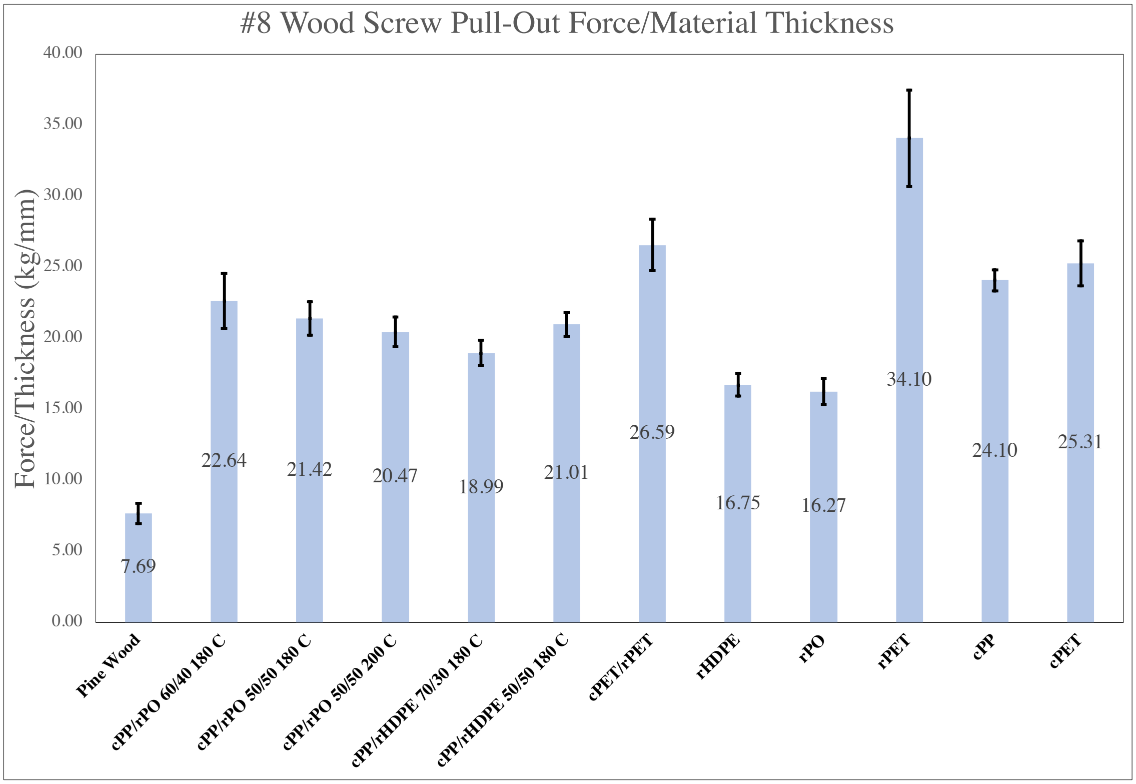

Figure 4.2: #8 wood screw pull-out force/material thickness averages.

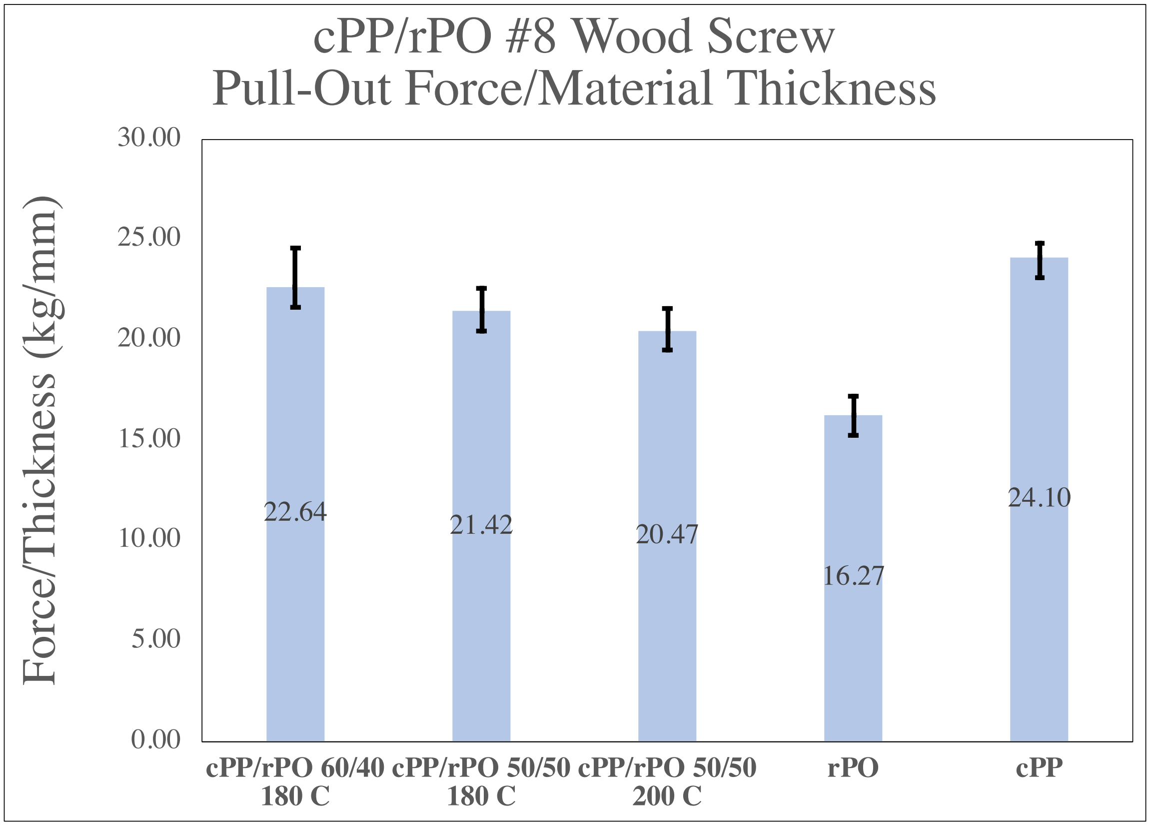

Figure 4.3: cPP/rPO #8 wood screw pull-out force/material thickness averages.

The cPP/rPO samples tested with #8 wood screws yielded an average pull-out resistance strength between cPP and rPO. For cPP/rPO samples, the 60/40 weight ratio compression molded at 180° C had the highest average pull-out resistance of 22.64 kg/mm.

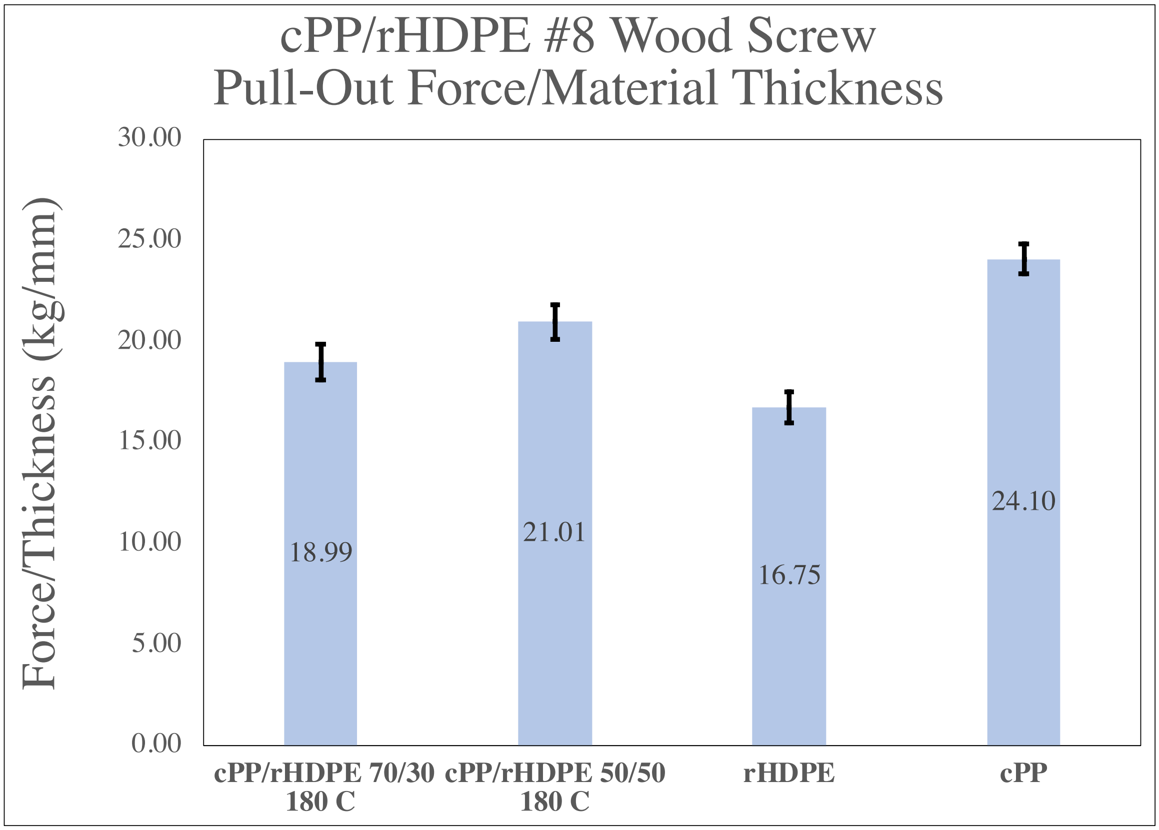

Figure 4.4: cPP/rHDPE #8 wood screw pull-out force/material thickness averages.

The cPP/rHDPE samples tested with #8 wood screws yielded an average pull-out resistance strength between cPP and rHDPE. For cPP/rHDPE samples, the 50/50 weight ratio compression molded at 180° C had the highest average pull-out resistance of 21.01 kg/mm.

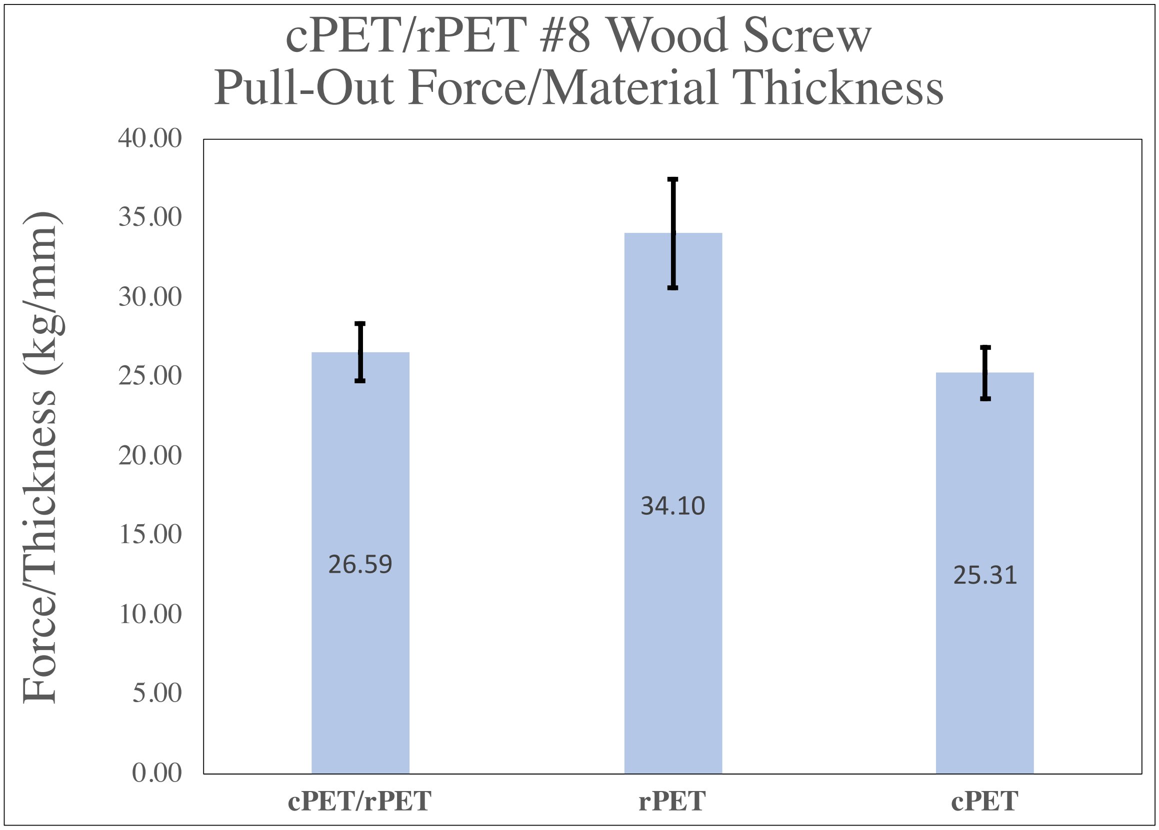

Figure 4.5: cPET/rPET #8 wood screw pull-out force/material thickness averages.

The cPET/rPET composite material tested with #8 wood screws had an average pull-out resistance strength of 26.59 kg/mm, which was between the cPET and rPET average pull-out resistance strengths.

Table 4.2: #8 Wood screw pull-out force/fastener contact area averages.

#8 Wood Screw Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	0.59	0.06	0.06
cPP/rPO 60/40 180 C	1.73	0.15	0.17
cPP/rPO 50/50 180 C	1.64	0.09	0.14
cPP/rPO 50/50 200 C	1.56	0.08	0.12
cPP/rHDPE 70/30 180 C	1.45	0.07	0.10
cPP/rHDPE 50/50 180 C	1.61	0.06	0.08
cPET/rPET	2.03	0.14	0.20
rHDPE	1.28	0.06	0.07
rPO	1.24	0.07	0.08
rPET	2.61	0.26	0.33
cPP	1.84	0.06	0.06
cPET	1.93	0.12	0.15

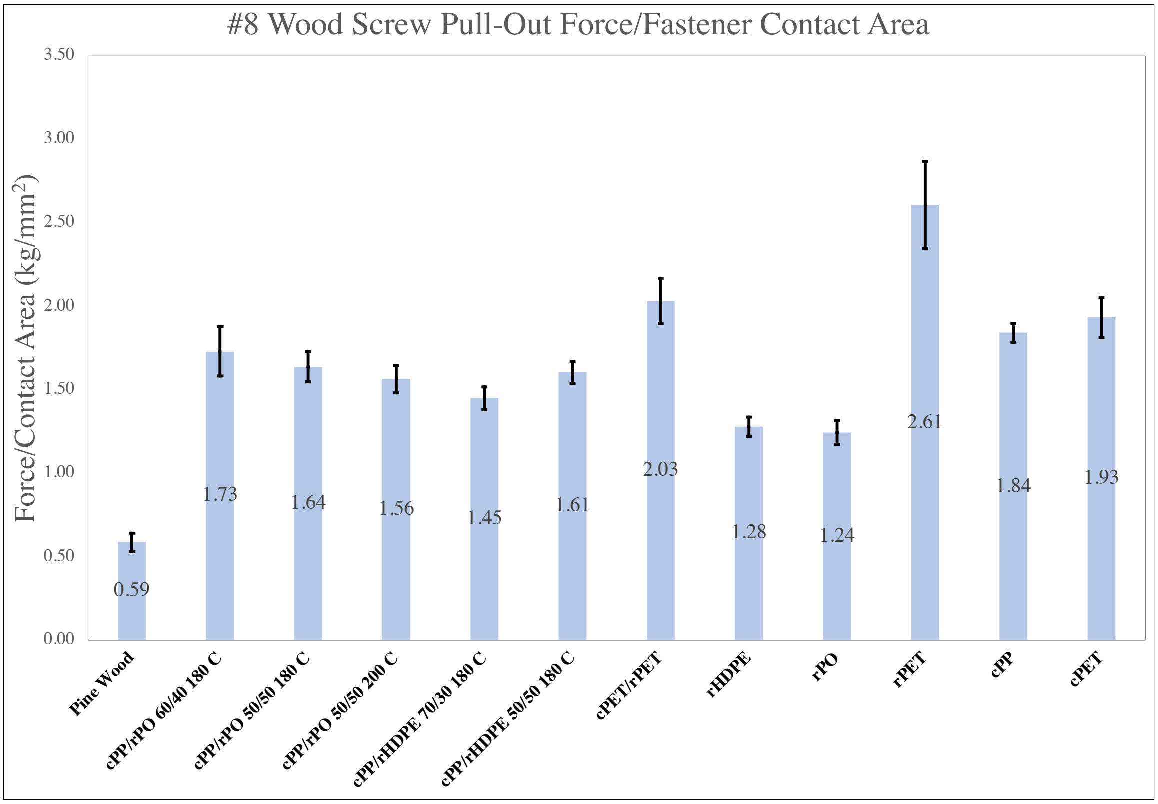

Figure 4.6: #8 wood screw pull-out force/fastener contact area averages.

The average pull-out resistance strength for #8 wood screws in all recycled composite materials was greater than the average pull-out resistance strength for pine wood. The average force required to pull a #8 wood screw from pine wood was 7.69

kg/mm or 0.59 kg/mm^2 of fastener contact area. The average pull-out strength of the recycled carpet composite materials ranged from 18.99 kg/mm up to 26.59 kg/mm of fastener engagement or 1.45 kg/mm^2 up to 2.03 kg/mm^2 of fastener contact area to pull-out a #8 wood screw with cPET/rPET requiring the most force per millimeter.

Table 4.3: #12 Wood screw pull-out force/material thickness averages.

#12 Wood Screw Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	13.77	2.39	2.73
cPP/rPO 60/40 180 C	41.82	2.05	2.33
cPP/rPO 50/50 180 C	40.28	0.99	1.13
cPP/rPO 50/50 200 C	33.65	1.51	1.72
cPP/rHDPE 70/30 180 C	39.03	1.62	1.85
cPP/rHDPE 50/50 180 C	40.87	0.38	0.44
cPET/rPET	46.00	5.04	6.30
rHDPE	30.87	0.91	1.03
rPO	26.71	0.71	0.89
rPET	54.39	4.97	6.71
cPP	26.48	0.50	0.57
cPET	25.29	2.15	2.45

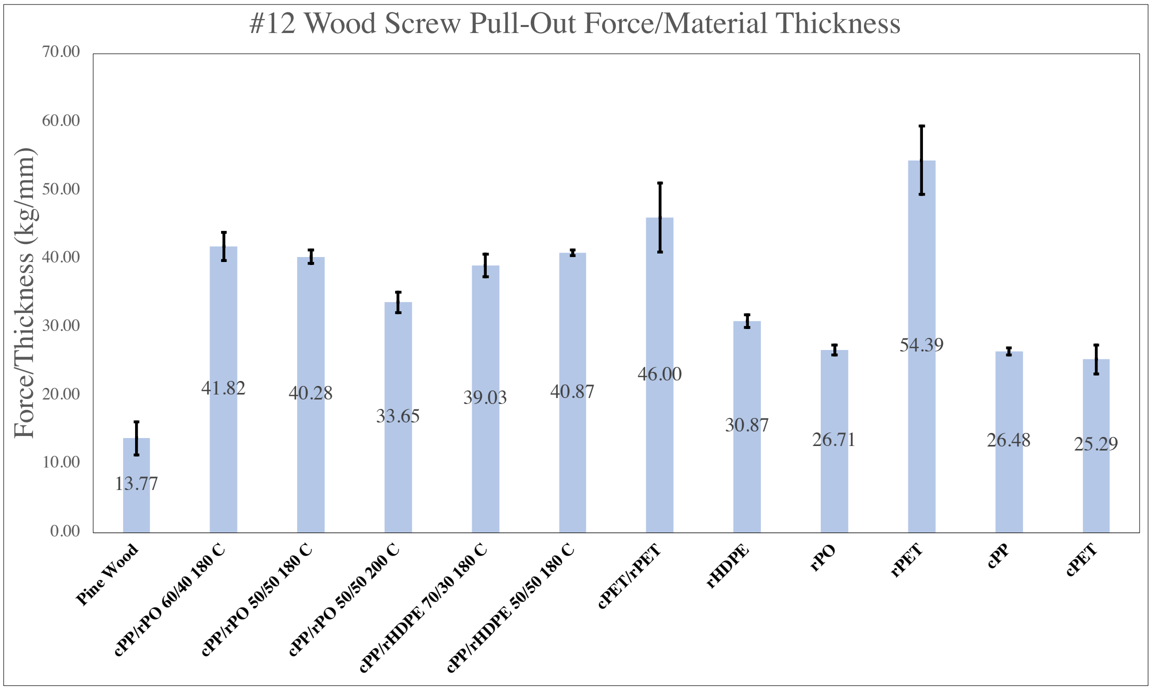

Figure 4.7: #12 wood screw pull-out force/material thickness area averages.

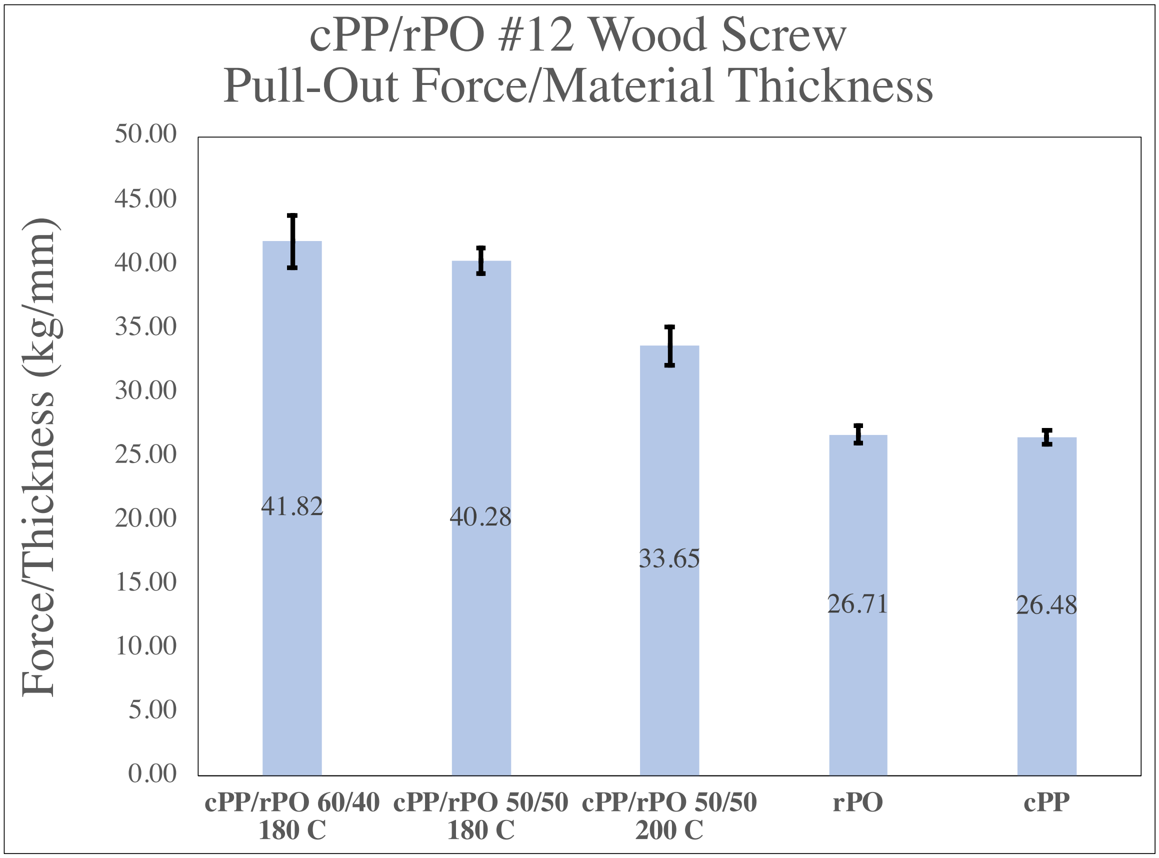

Figure 4.8: cPP/rPO #12 wood screw pull-out force/material thickness averages.

The cPP/rPO samples tested with #12 wood screws did not follow the rule of mixtures and had average pull-out resistance strengths greater than both rPO and cPP. The cPP/rPO samples with a 60/40 weight ratio compression molded at 180° C had the highest average pull-out resistance strength of 41.82 kg/mm compared to other cPP/rPO samples.

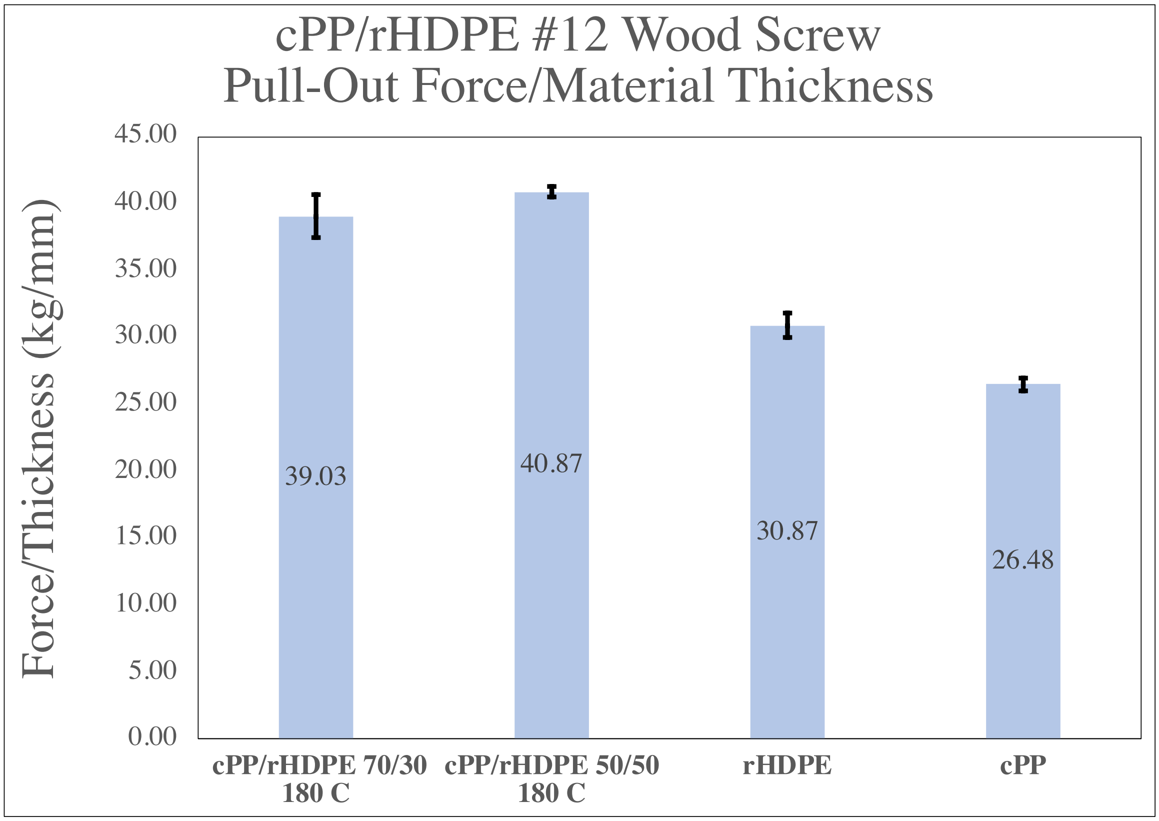

Figure 4.9: cPP/rHDPE #12 wood screw pull-out force/material thickness averages.

The cPP/rHDPE samples did not follow the rule of mixtures and had average pull-out resistance strengths greater than both rHDPE and cPP. The cPP/rHDPE samples with a 50/50 weight ratio compression molded at 180^{o} C had a slightly higher average pull-out resistance strength of 40.87 kg/mm compared to the average of the cPP/rHDPE samples with a 70/30 weight ratio compression molded at 180^{o} C.

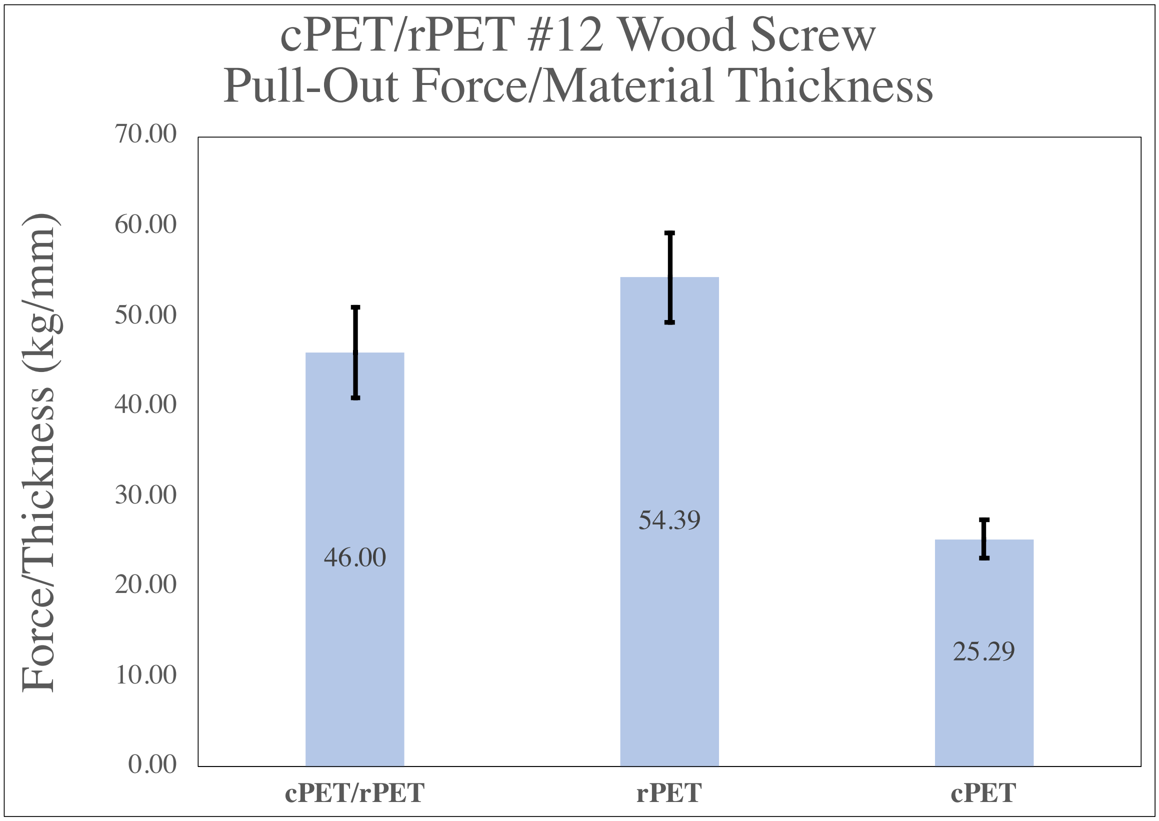

Figure 4.10: cPET/rPET #12 wood screw pull-out force/material thickness averages.

The cPET/rPET samples tested with #12 wood screws had an average pull-out resistance of 46.00 kg/mm, which was between the cPET and rPET average pull-out resistance strengths.

Table 4.4: #12 Wood screw pull-out force/fastener contact area averages.

#12 Wood Screw Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	0.79	0.14	0.16
cPP/rPO 60/40 180 C	2.40	0.12	0.13
cPP/rPO 50/50 180 C	2.31	0.06	0.06
cPP/rPO 50/50 200 C	1.93	0.09	0.10
cPP/rHDPE 70/30 180 C	2.24	0.09	0.11
cPP/rHDPE 50/50 180 C	2.35	0.02	0.02
cPET/rPET	2.64	0.29	0.36
rHDPE	1.77	0.05	0.06
rPO	1.53	0.04	0.05
rPET	3.12	0.28	0.38
cPP	1.52	0.03	0.03
cPET	1.45	0.12	0.14

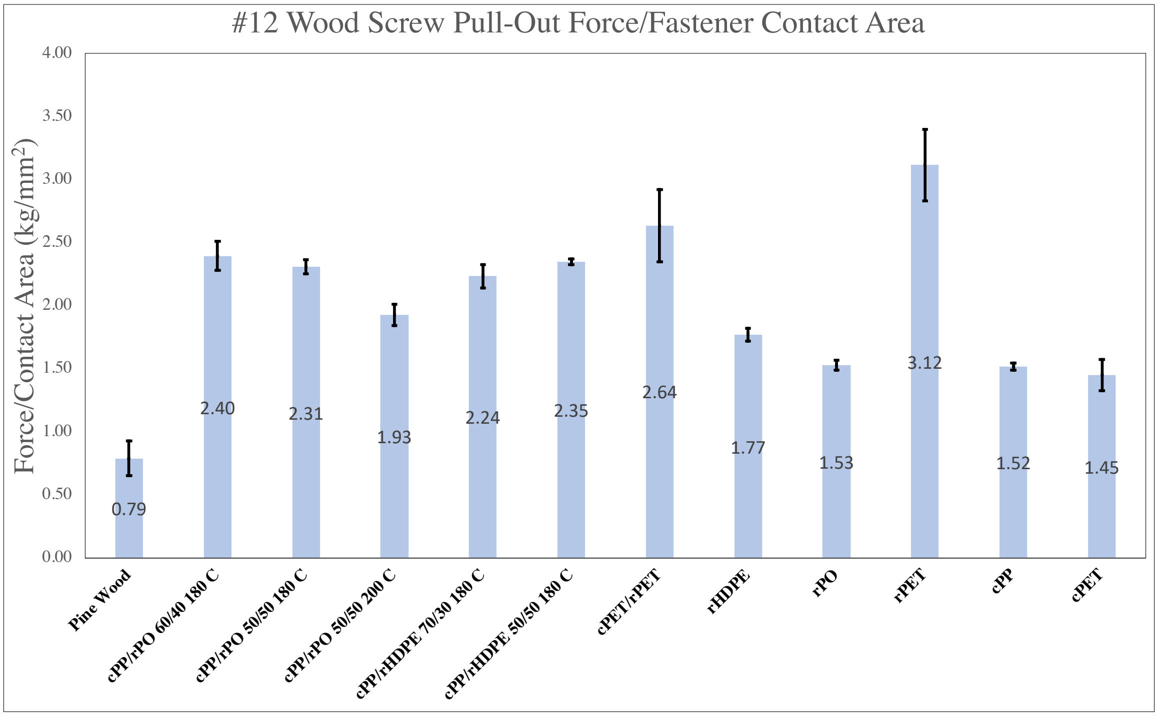

Figure 4.11: #12 wood screw pull-out force/fastener contact area averages.

For #12 wood screws, all recycled composite materials had greater pull-out resistance than pine wood. The force required to pull a #12 wood screw from pine wood was on average 13.77 kg/mm of fastener engagement or 0.79 kg/mm^2 of fastener contact area. The recycled carpet composite materials ranged from 33.65 kg/mm up to 46.00 kg/mm of fastener engagement or 1.93 kg/mm^2 up to 2.64 kg/mm^2 of fastener contact area to pull a #12 wood screw with cPET/rPET requiring the most force.

4.2 Bolts

Figure 4.12: 5/16-18 and 10-24 bolts.

Appropriately sized holes were drilled into the samples and threads cut into the holes using thread tapping tools. Bolts were then inserted into the tapped holes until the end of the bolt was past the material's bottom edge. Pine wood was not tested with bolts as the material was unable to have threads successfully cut into drilled holes.

The smaller of the two bolts used was 4.83 mm (0.1900″) in diameter (10-24 UNC Thread) measured at the widest portion of the threads while the larger bolt measured 7.94 mm (0.3125″) in diameter (5/16-18 UNC Thread).

Figure 4.13: Threaded hole in recycled composite material.

Table 4.5: 10-24 bolt pull-out force/material thickness averages.

10-24 Bolt Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
cPP/rPO 60/40 180 C	26.96	4.34	4.95
cPP/rPO 50/50 180 C	30.55	1.22	1.39
cPP/rPO 50/50 200 C	25.39	1.11	1.27
cPP/rHDPE 70/30 180 C	31.22	1.23	1.41
cPP/rHDPE 50/50 180 C	28.60	1.25	1.42
cPET/rPET	31.84	3.51	4.39
rHDPE	21.47	0.92	1.05
rPO	19.18	0.32	0.36
rPET	53.99	1.39	1.58
cPP	34.79	1.71	1.95
cPET	28.69	2.12	2.42

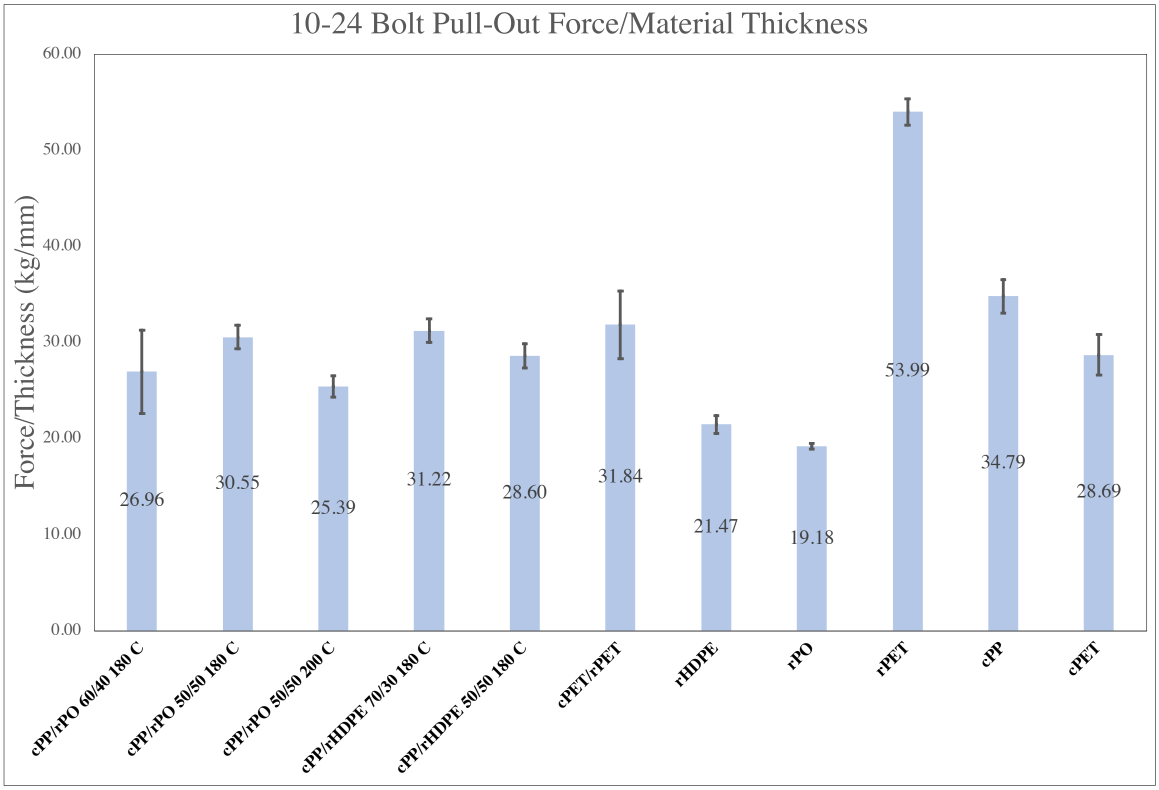

Figure 4.14: 10-24 bolt pull-out force/material thickness averages.

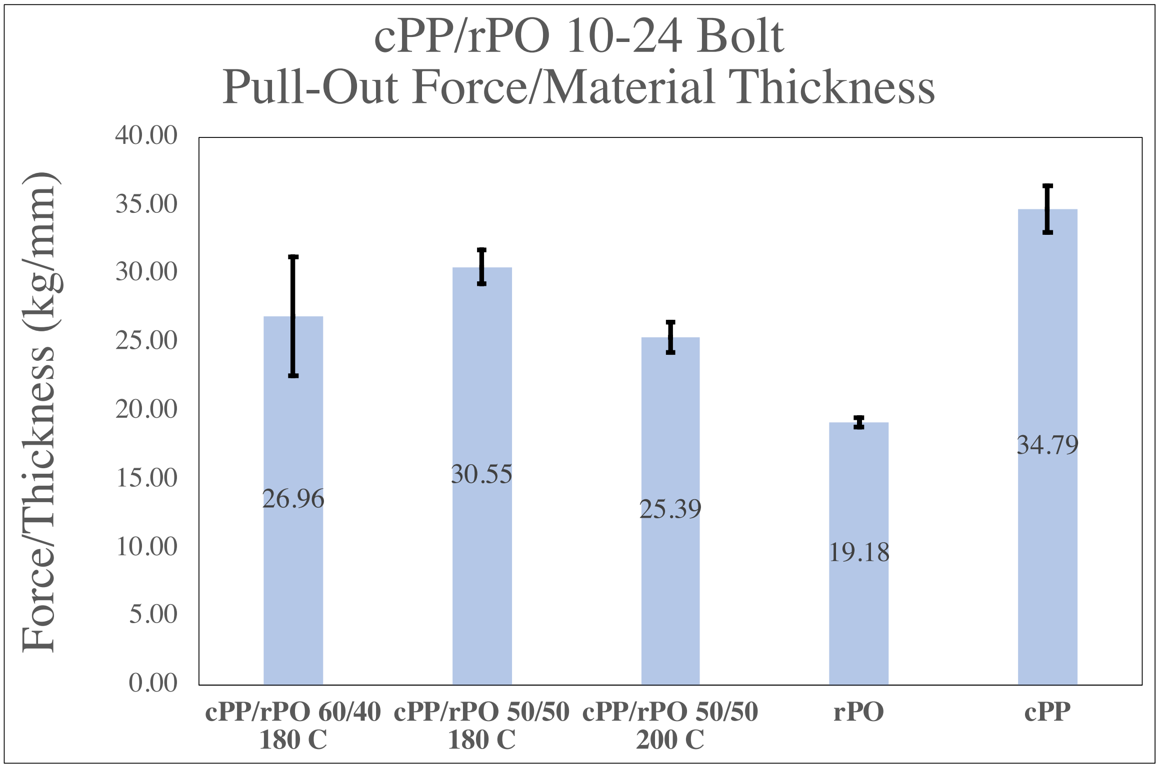

Figure 4.15: cPP/rPO 10-24 bolt pull-out force/material thickness averages.

The cPP/rPO samples tested with 10-24 bolts yielded an average pull-out resistance strength between cPP and rPO. For cPP/rPO samples, the 50/50 weight ratio compression molded at 180° C had the highest average pull-out resistance of 30.55 kg/mm.

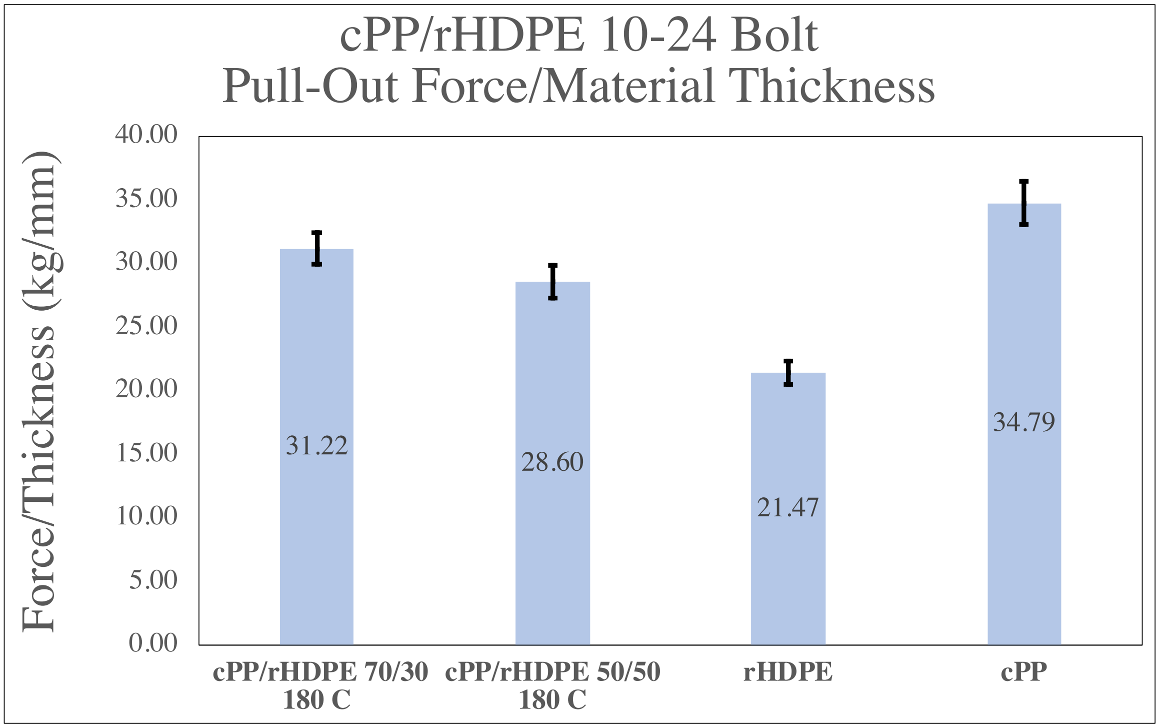

Figure 4.16: cPP/rHDPE 10-24 bolt pull-out force/material thickness averages.

The cPP/rHDPE samples tested with 10-24 bolts yielded an average pull-out resistance strength between cPP and rHDPE. For cPP/rHDPE samples, the 70/30 weight ratio compression molded at 180° C had the highest average pull-out resistance of 31.22 kg/mm.

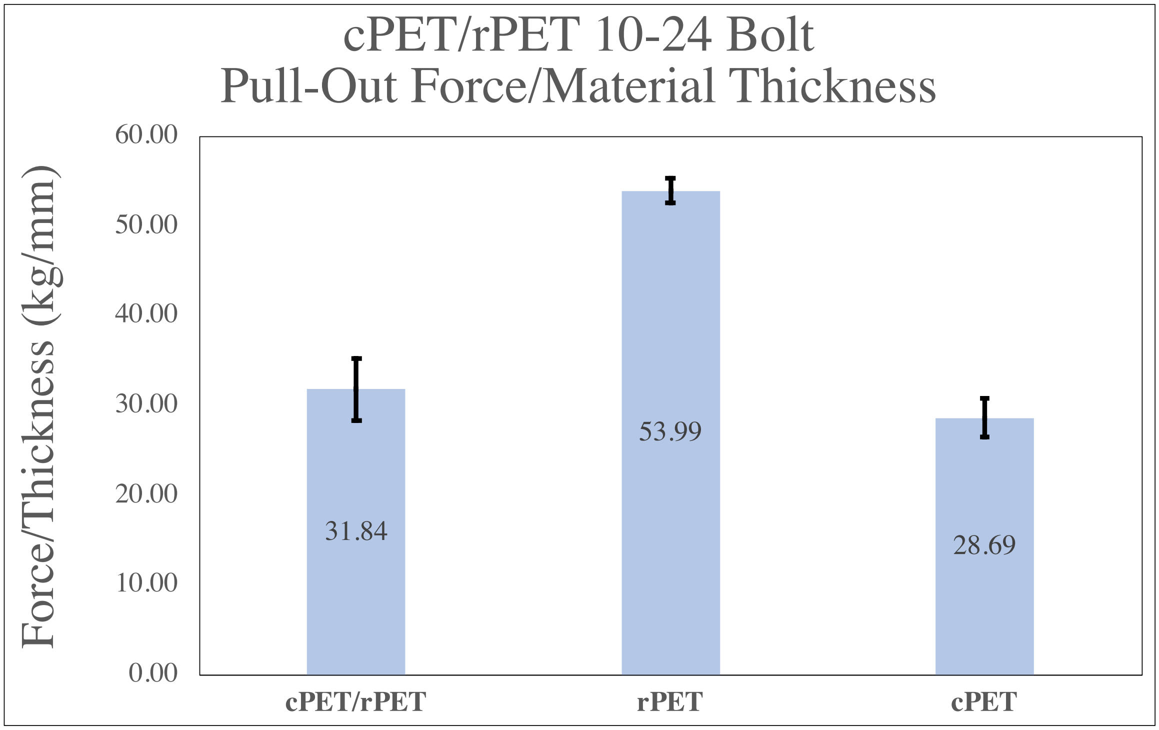

Figure 4.17: cPET/rPET 10-24 bolt pull-out force/material thickness averages.

The cPET/rPET composite material tested with 10-24 bolts had an average pull-out resistance strength of 31.84 kg/mm, which was between the cPET and rPET average pull-out resistance strengths, but only slightly above the average pull-out resistance strength of cPET only samples.

Table 4.6: 10-24 bolt pull-out force/fastener contact area averages.

10-24 Bolt Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
cPP/rPO 60/40 180 C	1.79	0.29	0.33
cPP/rPO 50/50 180 C	2.03	0.08	0.09
cPP/rPO 50/50 200 C	1.69	0.07	0.08
cPP/rHDPE 70/30 180 C	2.08	0.08	0.09
cPP/rHDPE 50/50 180 C	1.90	0.08	0.09
cPET/rPET	2.12	0.23	0.29
rHDPE	1.43	0.06	0.07
rPO	1.28	0.02	0.02
rPET	3.59	0.09	0.11
cPP	2.31	0.11	0.13
cPET	1.91	0.14	0.16

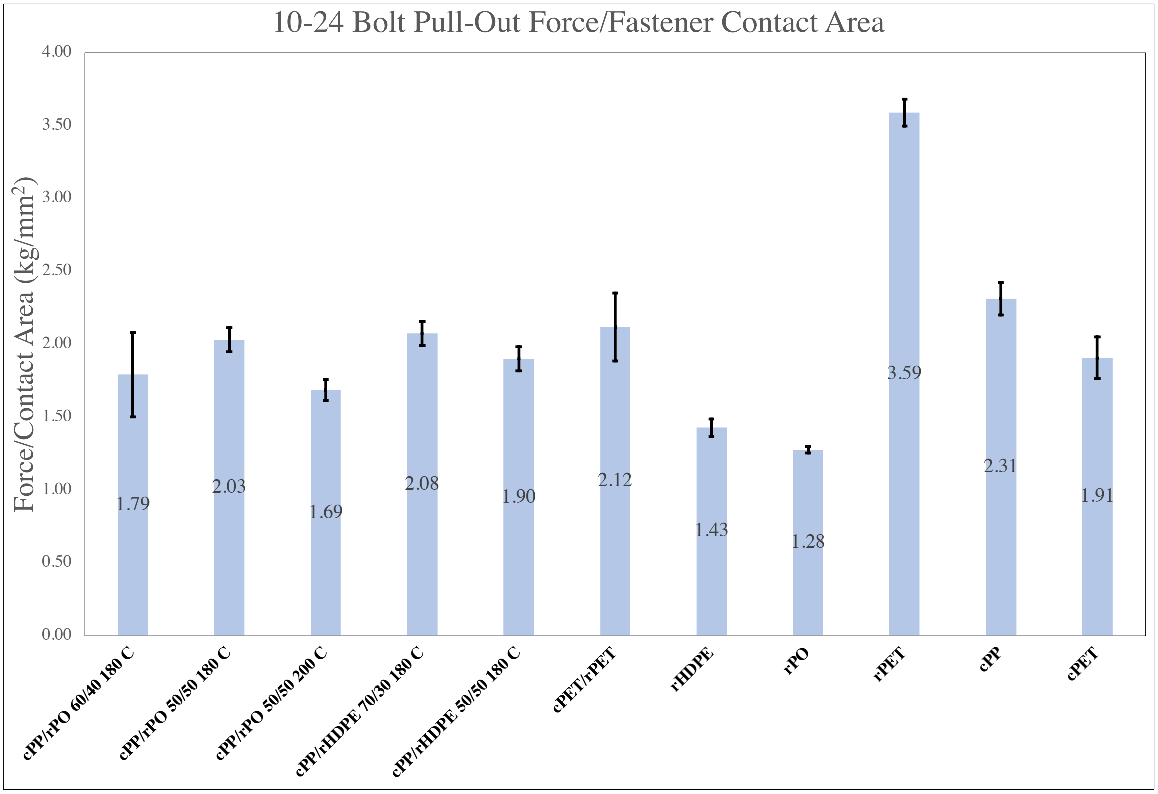

Figure 4.18: 10-24 bolt pull-out force/fastener contact area averages.

The cPP/rHDPE and cPP/rPO composites had greater pull-out resistance to 10-24 bolts than the plain resin rHDPE and rPO samples but a lower pull-out resistance than cPP only samples.

The cPET/rPET composite samples had a lower pull-out resistance to 10-24 bolts than the plain resin rPET samples but a higher pull-out resistance than cPET only samples.

Table 4.7: 5/16-18 bolt pull-out force/material thickness averages.

5/16-18 Bolt Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
cPP/rPO 60/40 180 C	44.45	1.66	1.89
cPP/rPO 50/50 180 C	38.77	1.74	1.98
cPP/rPO 50/50 200 C	27.59	1.62	2.02
cPP/rHDPE 70/30 180 C	35.20	4.24	4.83
cPP/rHDPE 50/50 180 C	34.82	2.83	3.23
cPET/rPET	53.73	2.48	3.09
rHDPE	29.55	1.36	1.84
rPO	27.13	0.48	0.55
rPET	69.96	3.93	4.48
cPP	46.98	3.49	3.98
cPET	42.63	3.76	4.70

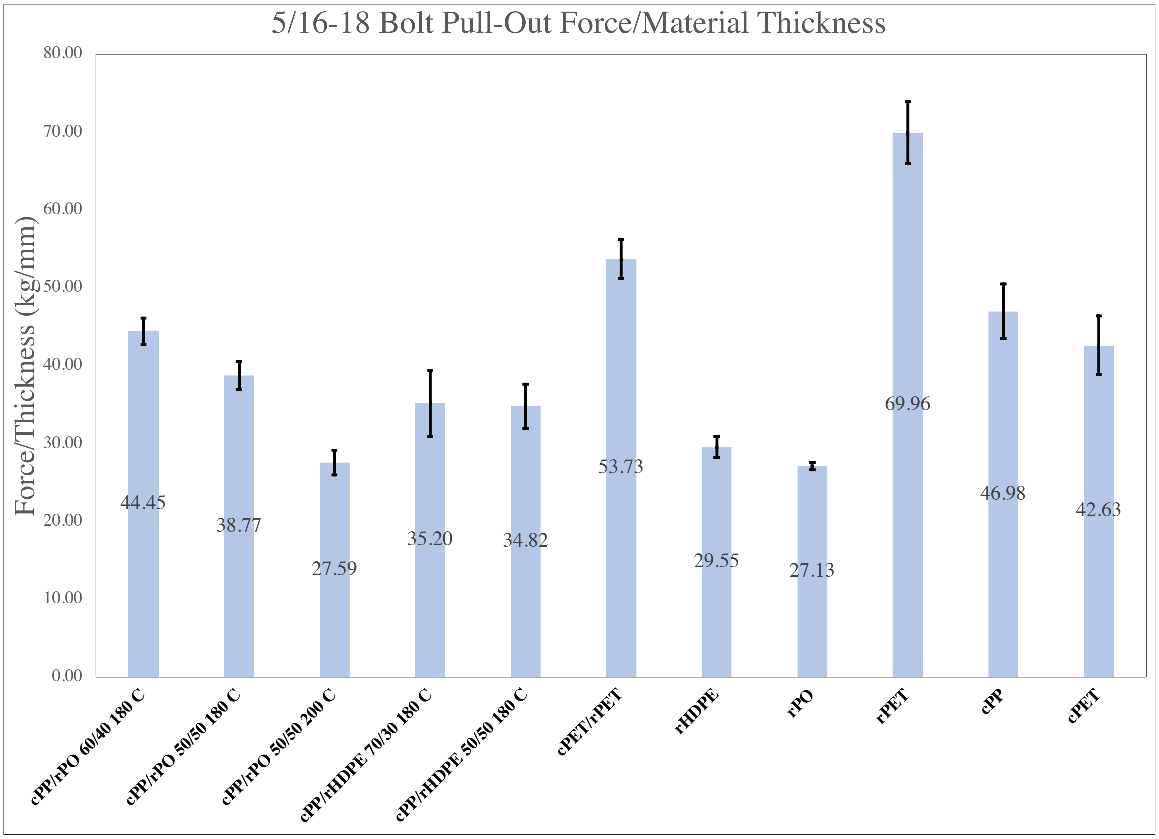

Figure 4.19: 5/16-18 bolt pull-out force/material thickness averages.

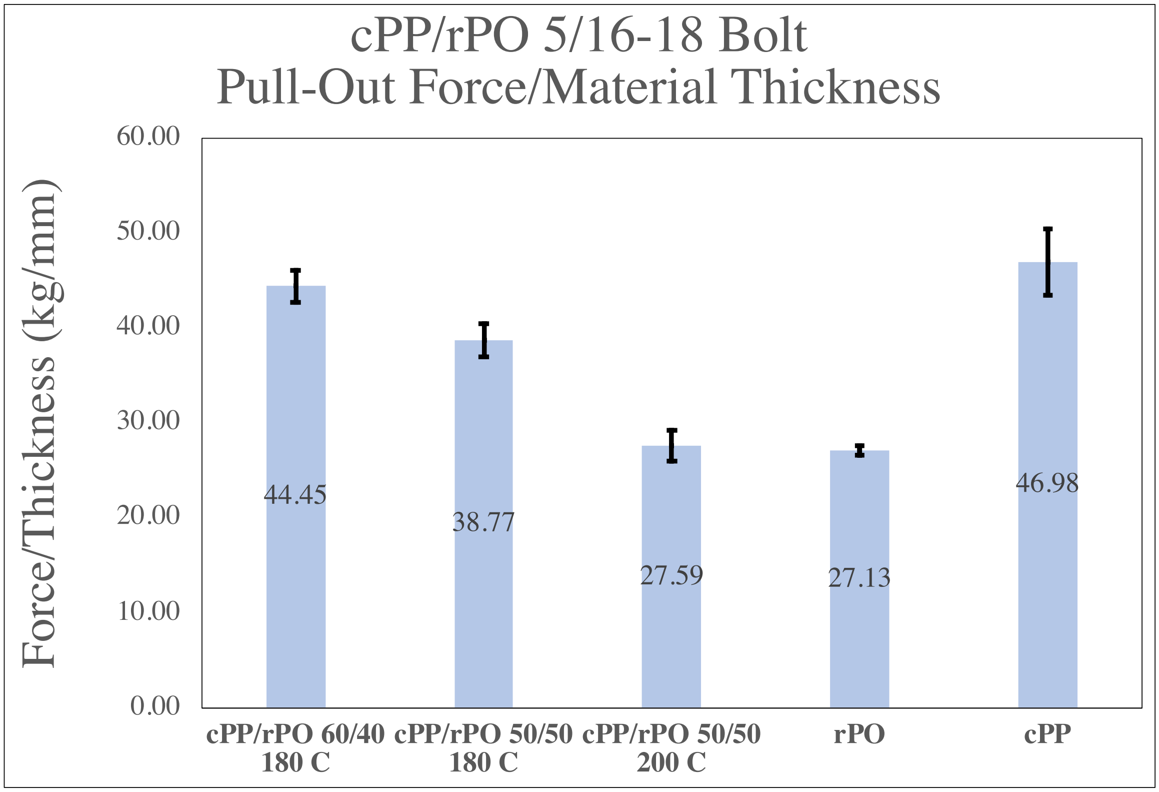

Figure 4.20: cPP/rPO 5/16-18 bolt pull-out force/material thickness averages.

The cPP/rPO samples tested with5/16-18 bolts yielded an average pull-out resistance strength between cPP and rPO, but the cPP/rPO samples with a 50/50 weight ratio molded at 200^{o} C had an average pull-out resistance strength that was not significantly higher than the pull-out resistance strength for rPO. For cPP/rPO samples, the 60/40 weight ratio compression molded at 180^{o} C had the highest average pull-out resistance of 44.45 kg/mm. We can see that molding the cPP/rPO composites at a higher temperature negatively effects the pull-out resistance strength of the composite.

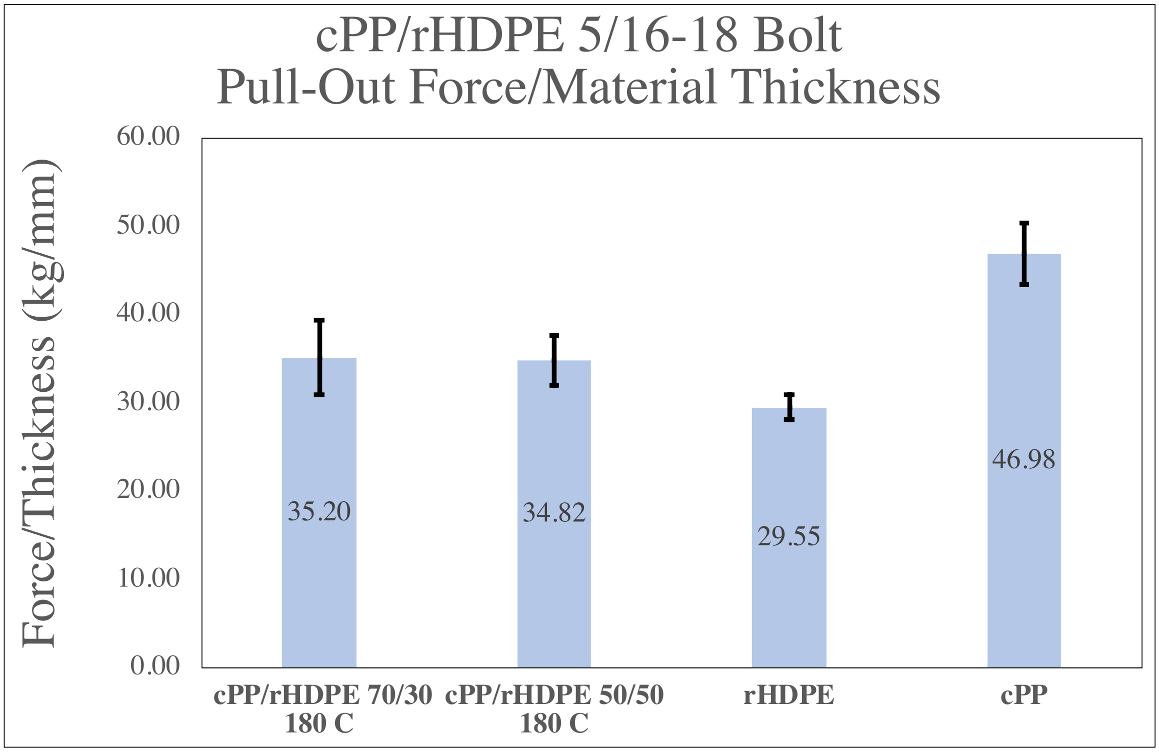

Figure 4.21: cPP/rHDPE 5/16-18 bolt pull-out force/material thickness averages.

The cPP/rHDPE samples tested with 15/16-18 bolts yielded an average pull-out resistance strength between cPP and rHDPE. For cPP/rHDPE samples, the 70/30 weight ratio compression molded at 180° C had the highest average pull-out resistance of 35.20 kg/mm.

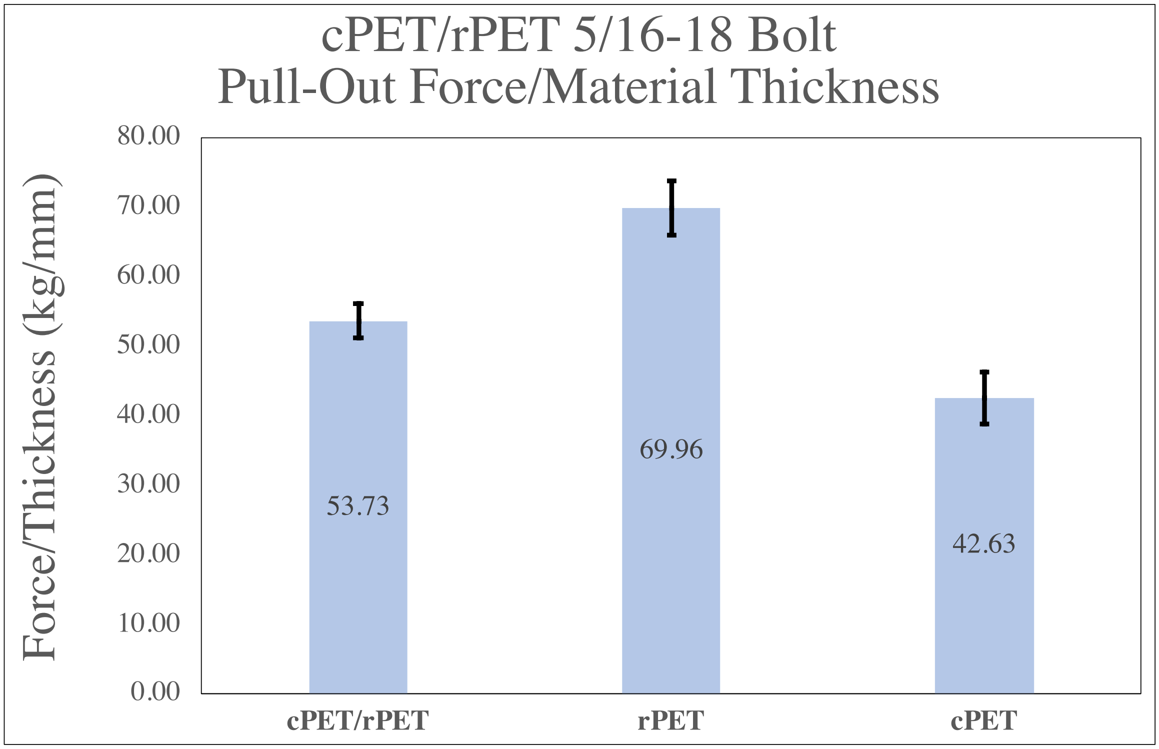

Figure 4.22: cPET/rPET 5/16-18 bolt pull-out force/material thickness averages.

The cPET/rPET composite material tested with 5/16-18 bolts had an average pull-out resistance strength of 53.73 kg/mm, which was between the cPET and rPET average pull-out resistance strengths.

Table 4.8: 5/16-18 bolt pull-out force/fastener contact area averages.

5/16-18 Bolt Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
cPP/rPO 60/40 180 C	1.81	0.07	0.08
cPP/rPO 50/50 180 C	1.58	0.07	0.08
cPP/rPO 50/50 200 C	1.12	0.07	0.08
cPP/rHDPE 70/30 180 C	1.43	0.17	0.20
cPP/rHDPE 50/50 180 C	1.42	0.12	0.13
cPET/rPET	2.19	0.10	0.13
rHDPE	1.20	0.06	0.07
rPO	1.10	0.02	0.02
rPET	2.85	0.16	0.18
cPP	1.91	0.14	0.16
cPET	1.74	0.15	0.19

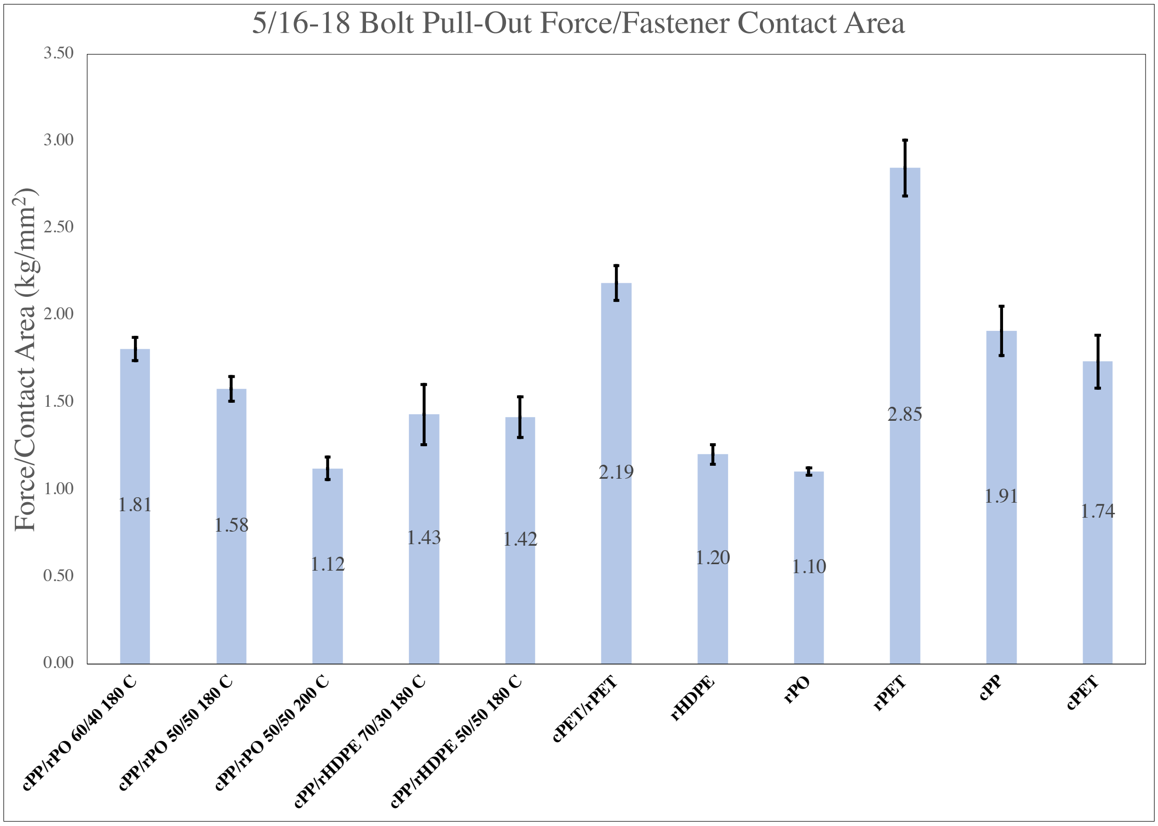

Figure 4.23: 5/16-18 bolt pull-out force/fastener contact area averages.

The cPP/rHDPE and cPP/rPO composites had greater pull-out resistance to 5/16-18 bolts than the plain resin rHDPE and rPO samples but a lower pull-out resistance than cPP only samples.

The cPET/rPET composite samples had a lower pull-out resistance to 5/16-18 bolts than the plain resin rPET samples but a higher pull-out resistance than cPET only samples.

When comparing pull-out force with fastener contact area it can be seen that all the materials except for the cPP/rPO 60/140 180^{o} C had higher values for the smaller 10-24 bolts than the 5/16-18 bolts.

4.3 Nails

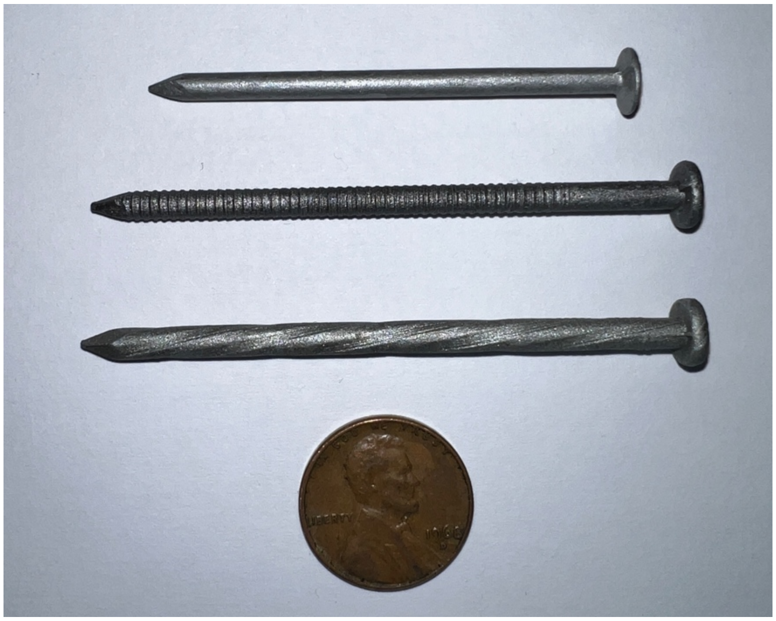

Figure 4.24: Common nail, ring shank nail, and spiral shank nail.

Three different types of nails were used in this study. Common nails were selected because they are the most popular nails used across industry and ring and spiral shank nails were chosen because of their use in pallet making. Nails were pounded into samples using a common woodworking hammer so that the tip of the nail was completely through the sample. Composite samples with cPET cracked when driving a nail into 50 mm x 50 mm samples and could not be tested.

The shank diameter of all 3 nail types varied from one another. Common nails had a shank diameter of 2.95 mm (0.1161″), ring shank nails had a shank diameter of 3.15 mm (0.1240″), and spiral shank nails had a diameter of 3.50 mm (0.1378″).

Ribbed shank nails had the greatest pull-out resistance of the 3 nail types for all materials tested except for pine wood. Spiral shank nails were the next strongest and common nails had the lowest pull-out resistance.

Table 4.9: Common nail pull-out force/material thickness averages.

Common Nail Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	0.71	0.02	0.03
cPP/rPO 60/40 180 C	5.23	0.37	0.46
cPP/rPO 50/50 180 C	4.55	0.52	0.65
cPP/rPO 50/50 200 C	5.08	0.48	0.55
cPP/rHDPE 70/30 180 C	5.25	0.25	0.29
cPP/rHDPE 50/50 180 C	4.48	0.24	0.27
rHDPE	5.02	0.34	0.38
rPO	3.07	0.39	0.44
cPP	7.08	0.62	0.70

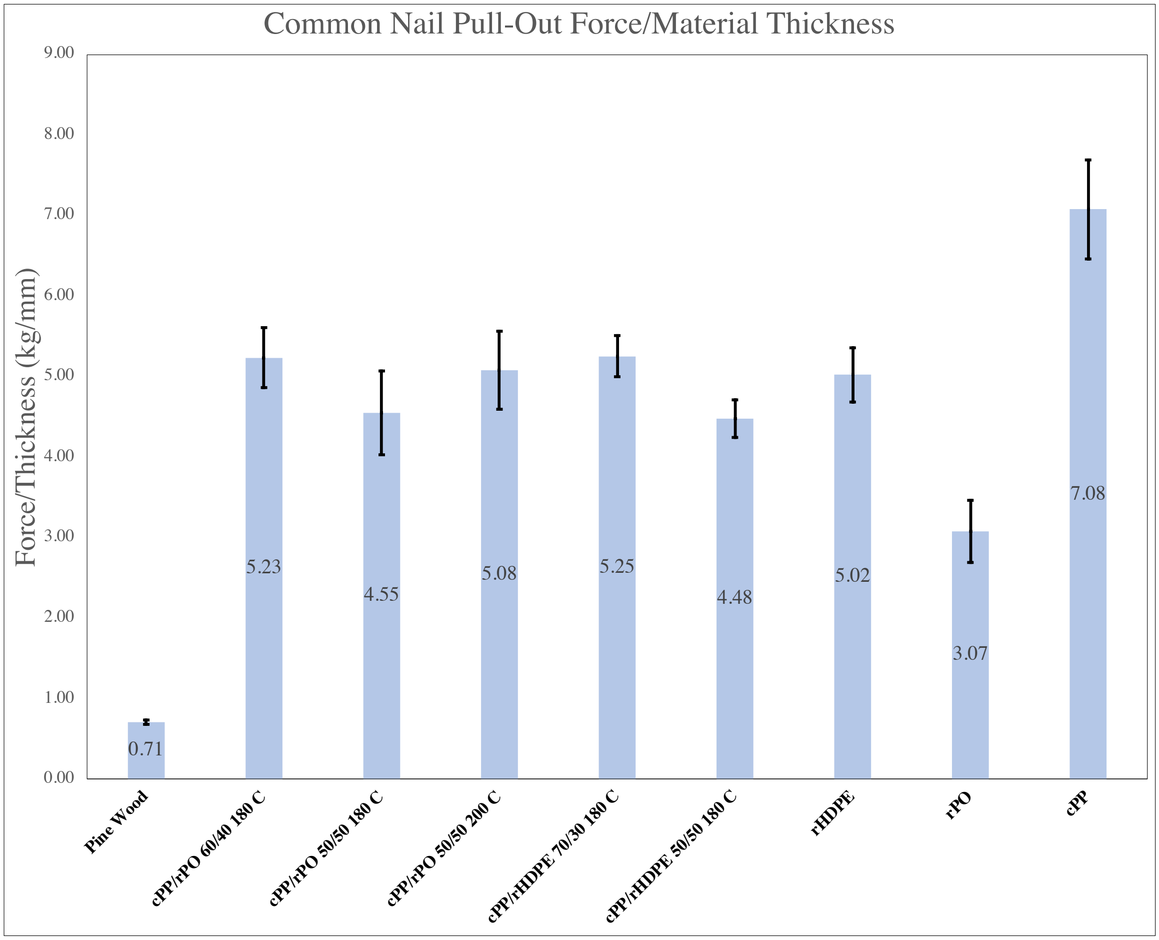

Figure 4.25: Common nail pull-out force/material thickness averages.

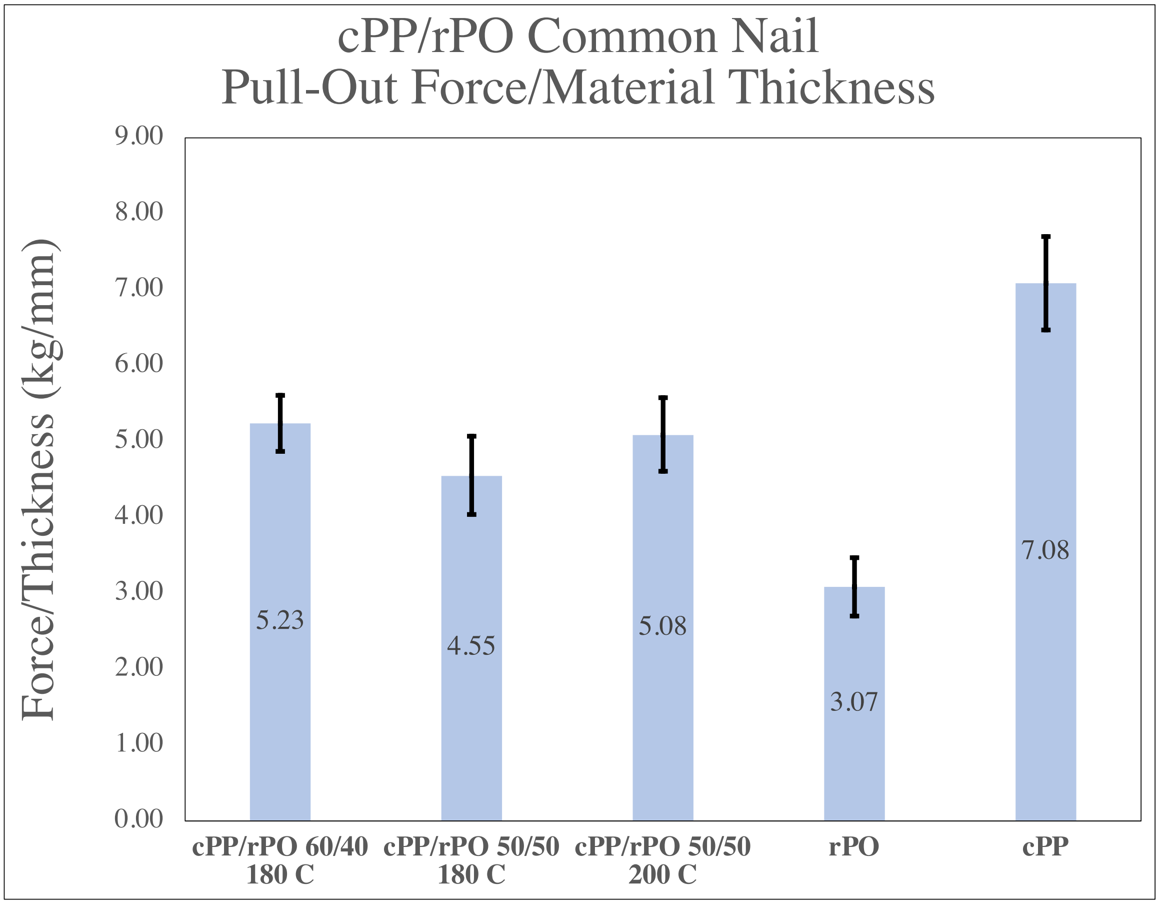

Figure 4.26: cPP/rPO common nail pull-out force/material thickness averages.

The cPP/rPO samples tested with common nails yielded an average pull-out resistance strength between cPP and rPO. For cPP/rPO samples, the 60/40 weight ratio compression molded at 180° C had the highest average pull-out resistance of 5.23 kg/mm.

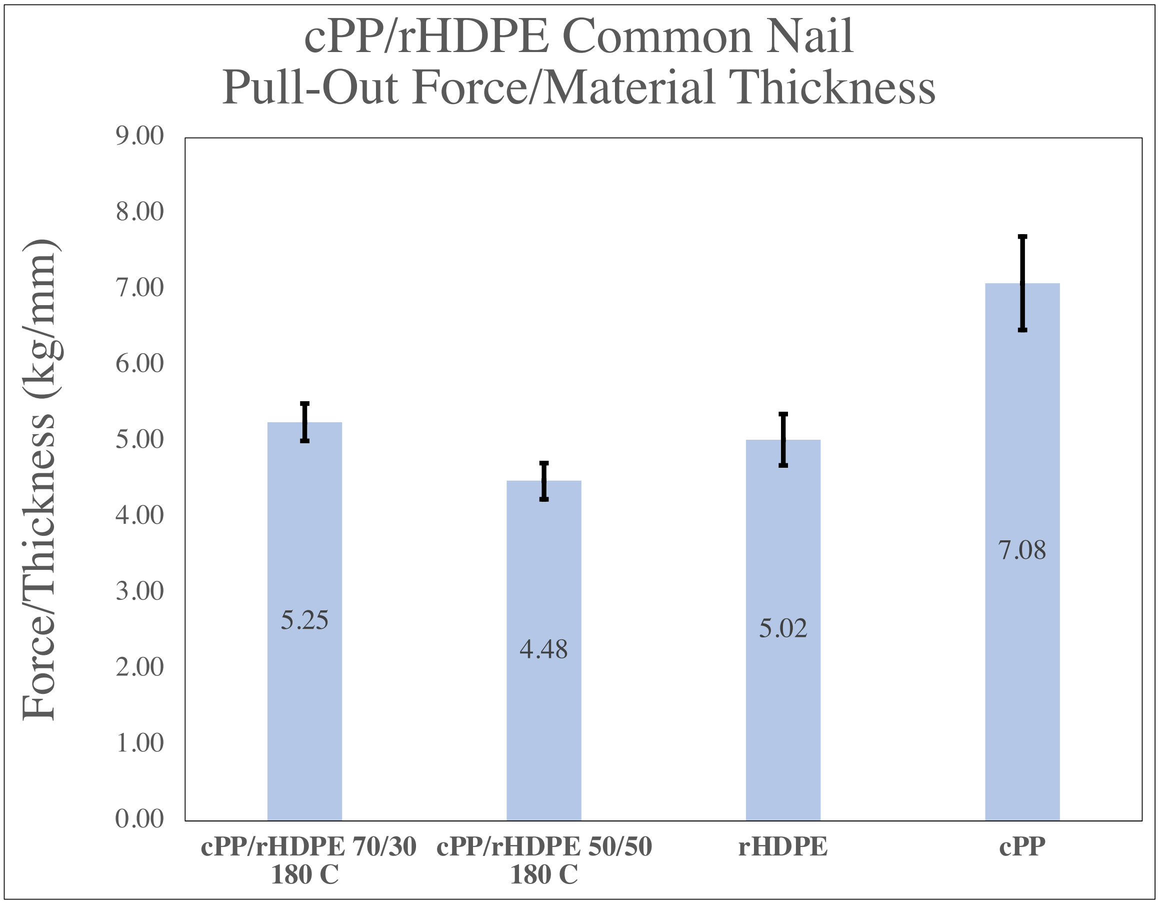

Figure 4.27: cPP/rHDPE common nail pull-out force/material thickness averages.

Out of the cPP/rHDPE samples tested with common nails, only the samples with a 70/30 mass ratio, molded at 180° C, had an average pull-out resistance strength between rHDPE and cPP. The cPP/rHDPE samples with a 50/50 mass ratio molded at 180° C had an average pull-out resistance strength lower than both rHDPE and cPP. Of the cPP/rHDPE samples, the samples with a 70/30 weight ratio molded at 180° C had the higher average pull-out resistance strength of the two composites at 5.25 kg/mm.

Table 4.10: Common nail pull-out force/fastener contact area averages.

Common Nail Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	0.08	0.00	0.00
cPP/rPO 60/40 180 C	0.56	0.04	0.05
cPP/rPO 50/50 180 C	0.49	0.06	0.07
cPP/rPO 50/50 200 C	0.55	0.05	0.06
cPP/rHDPE 70/30 180 C	0.57	0.03	0.03
cPP/rHDPE 50/50 180 C	0.48	0.03	0.03
rHDPE	0.54	0.04	0.04
rPO	0.33	0.04	0.05
cPP	0.76	0.07	0.08

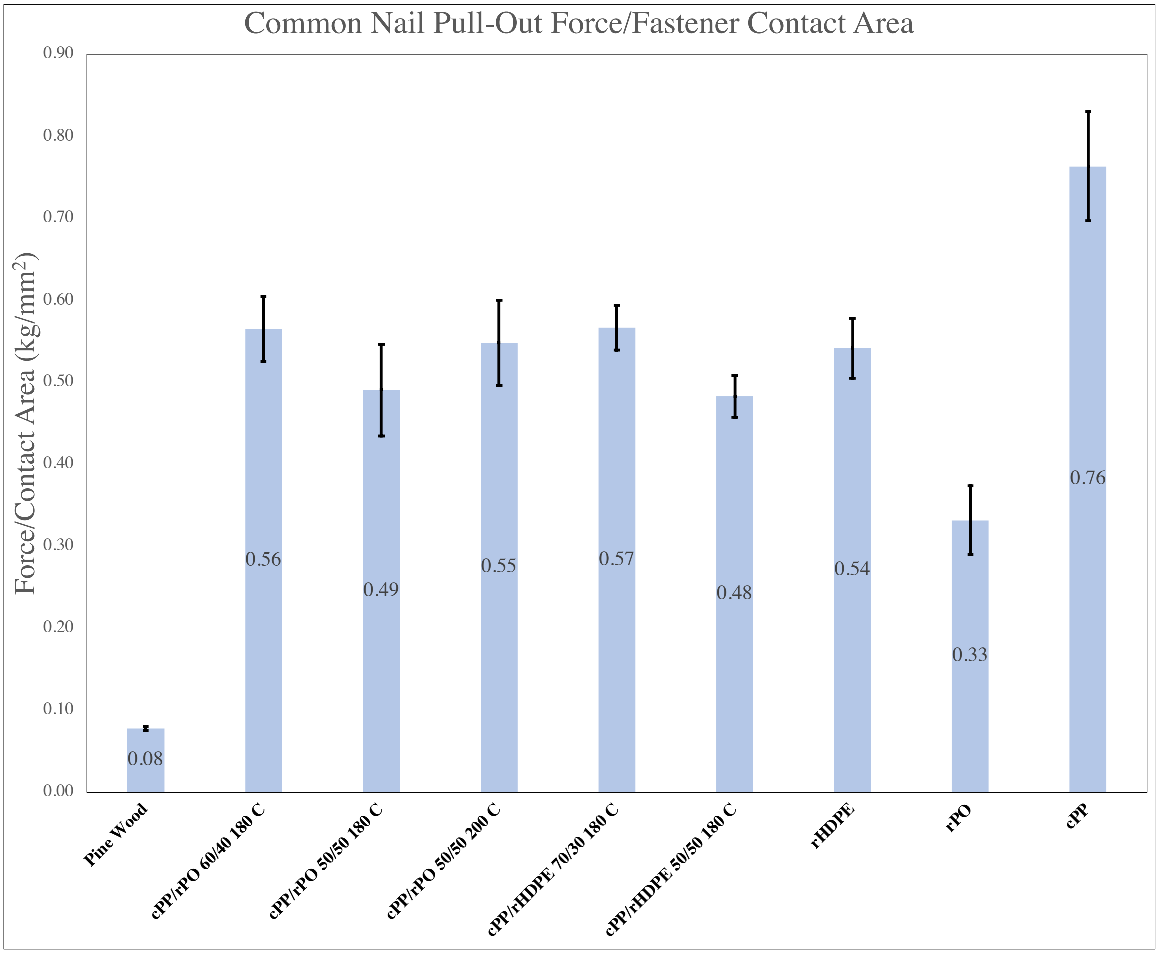

Figure 4.28: Common nail pull-out force/fastener contact area averages.

For common nails, all composite samples had greater pull-out resistances then pine wood.

Table 4.11: Ring shank nail pull-out force/material thickness averages.

Ring Shank Nail Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	2.30	0.34	0.39
cPP/rPO 60/40 180 C	9.48	1.19	1.48
cPP/rPO 50/50 180 C	8.48	0.69	0.79
cPP/rPO 50/50 200 C	5.84	0.77	1.04
cPP/rHDPE 70/30 180 C	9.51	0.93	1.06
cPP/rHDPE 50/50 180 C	8.87	0.70	0.87
rHDPE	8.54	0.72	0.82
rPO	5.30	0.66	0.75
cPP	12.63	1.36	1.70

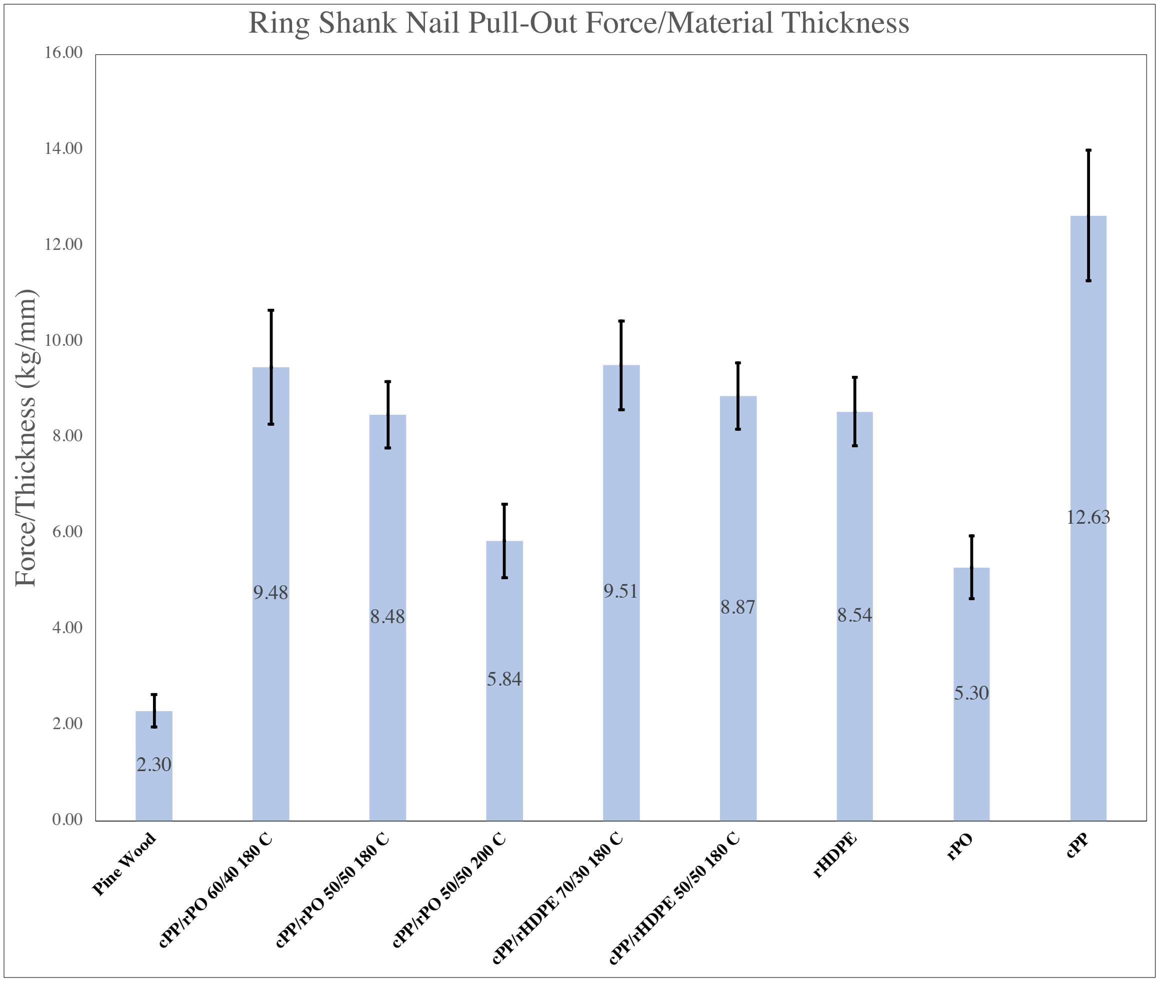

Figure 4.29: Ring shank nail pull-out force/material thickness averages.

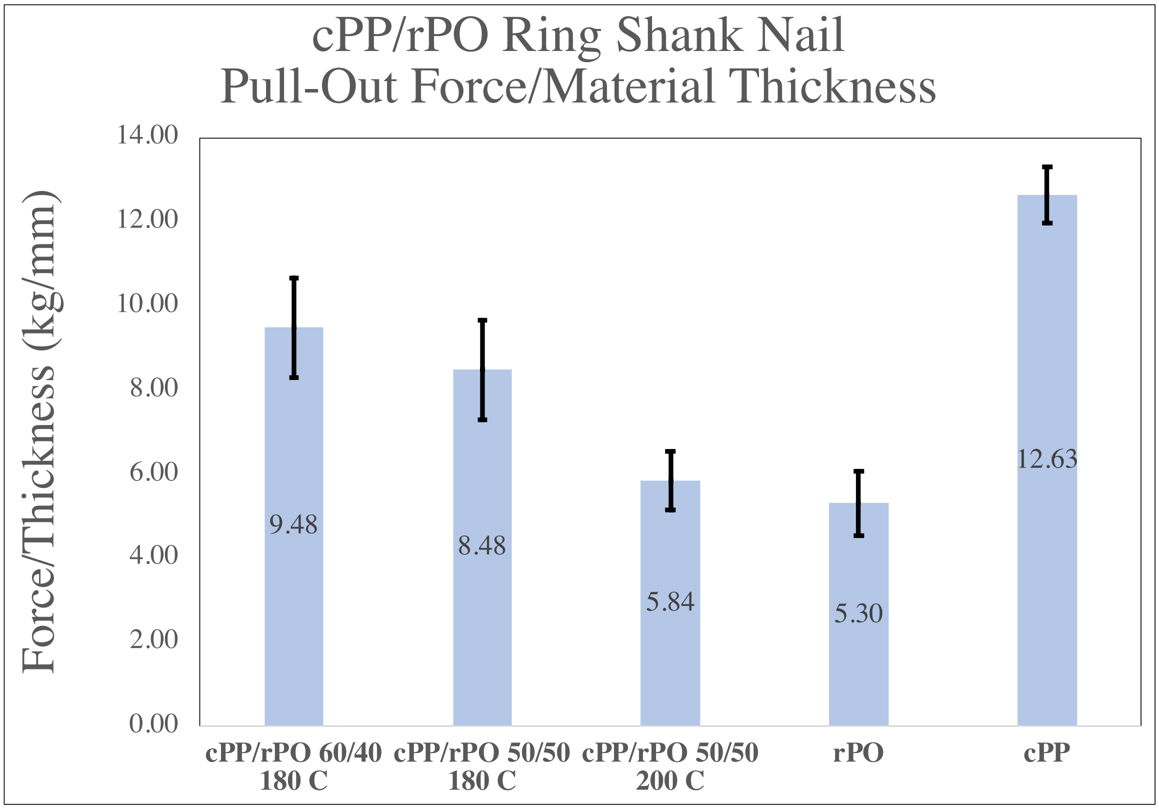

Figure 4.30: cPP/rPO ring shank nail pull-out force/material thickness averages.

The cPP/rPO samples tested with ring shank nails yielded an average pull-out resistance strength between cPP and rPO. For cPP/rPO samples, the 60/40 mass ratio compression molded at 180^{o} C had the highest average pull-out resistance of 9.48 kg/mm.

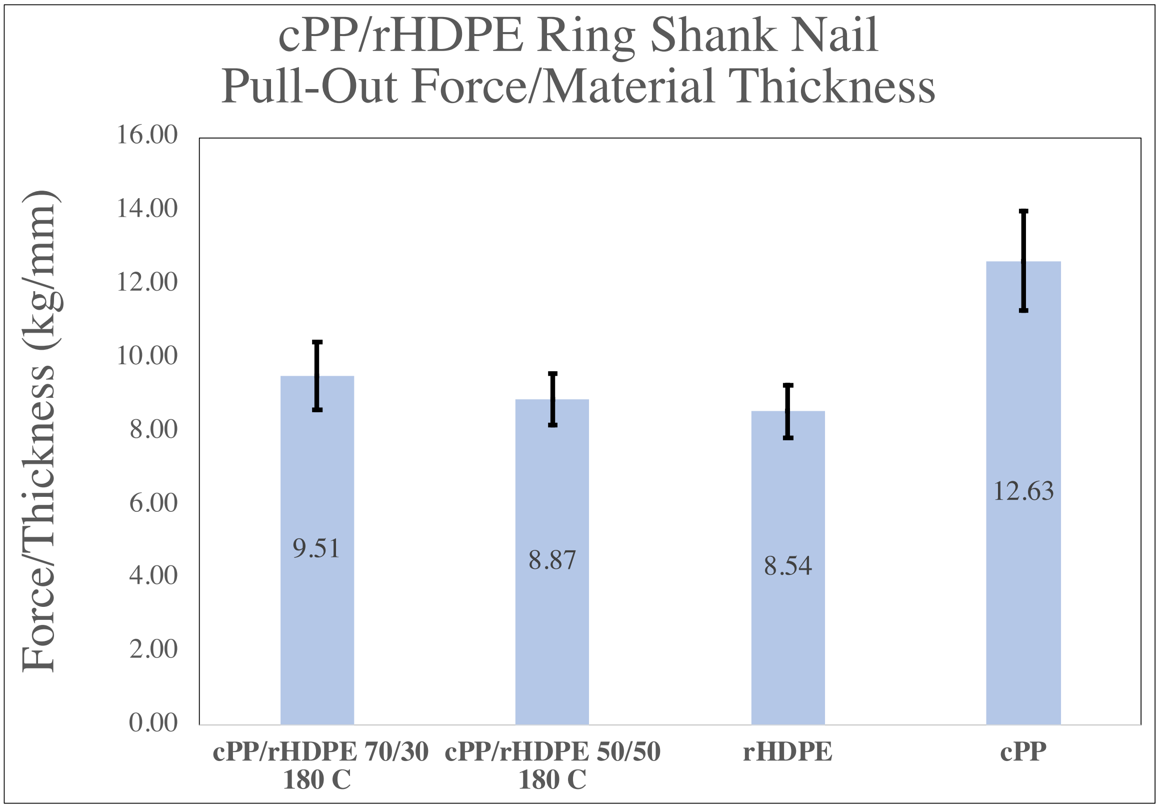

Figure 4.31: cPP/rHDPE ring shank nail pull-out force/material thickness averages.

The cPP/rHDPE samples tested with ring shank nails yielded an average pull-out resistance strength between cPP and rPO. For cPP/rHDPE samples, the 70/30 mass ratio compression molded at 180^{o} C had the highest average pull-out resistance of 9.51 kg/mm.

Table 4.12: Ring shank nail pull-out force/fastener contact area averages.

Ring Shank Nail Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	0.23	0.01	0.01
cPP/rPO 60/40 180 C	0.96	0.12	0.15
cPP/rPO 50/50 180 C	0.86	0.07	0.08
cPP/rPO 50/50 200 C	0.59	0.08	0.10
cPP/rHDPE 70/30 180 C	0.96	0.09	0.11
cPP/rHDPE 50/50 180 C	0.90	0.07	0.09
rHDPE	0.86	0.07	0.08
rPO	0.54	0.07	0.08
cPP	1.28	0.14	0.17

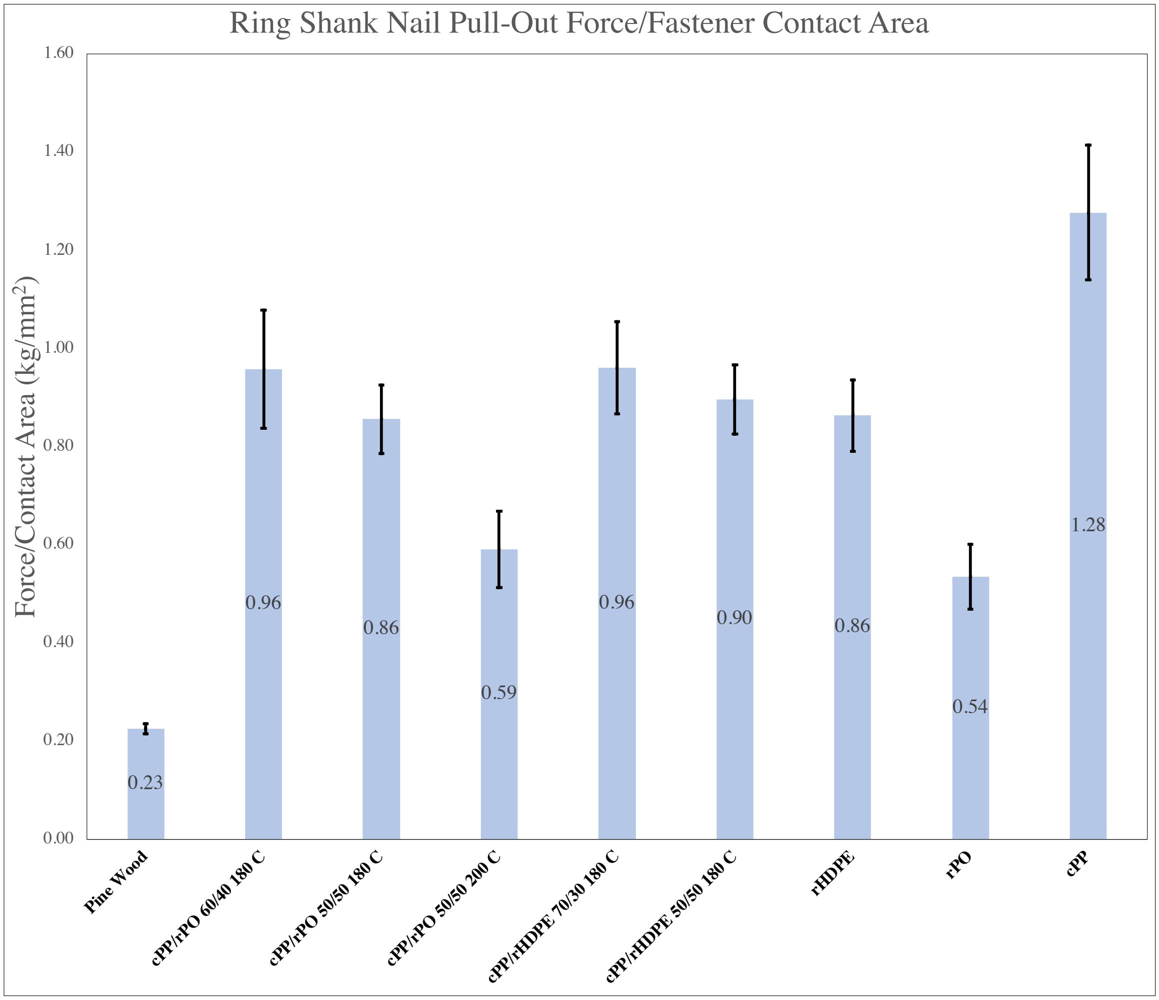

Figure 4.32: Ring shank nail pull-out force/fastener contact area averages.

For ring shank nails, all composite samples had greater pull-out resistances then pine wood.

Table 4.13: Spiral shank nail pull-out force/material thickness averages.

Spiral Shank Nail Pull-Out Force/Material Thickness			
Composition	**Force/Thickness (kg/mm)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	2.90	0.11	0.12
cPP/rPO 60/40 180 C	6.44	0.33	0.38
cPP/rPO 50/50 180 C	6.41	0.43	0.49
cPP/rPO 50/50 200 C	5.60	0.40	0.45
cPP/rHDPE 70/30 180 C	7.37	0.29	0.33
cPP/rHDPE 50/50 180 C	6.70	0.49	0.56
rHDPE	6.84	0.17	0.20
rPO	4.06	0.36	0.41
cPP	9.79	0.35	0.40

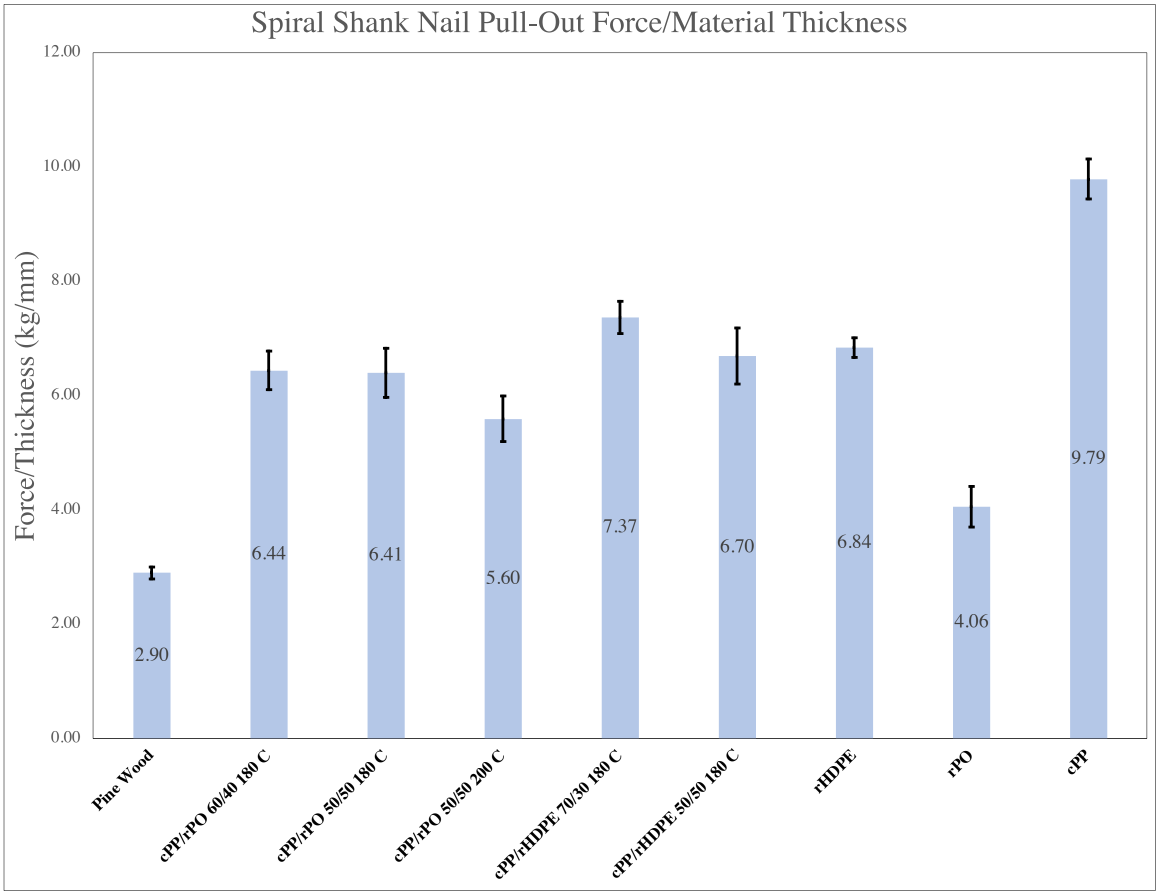

Figure 4.33: Spiral shank nail pull-out force/material thickness averages.

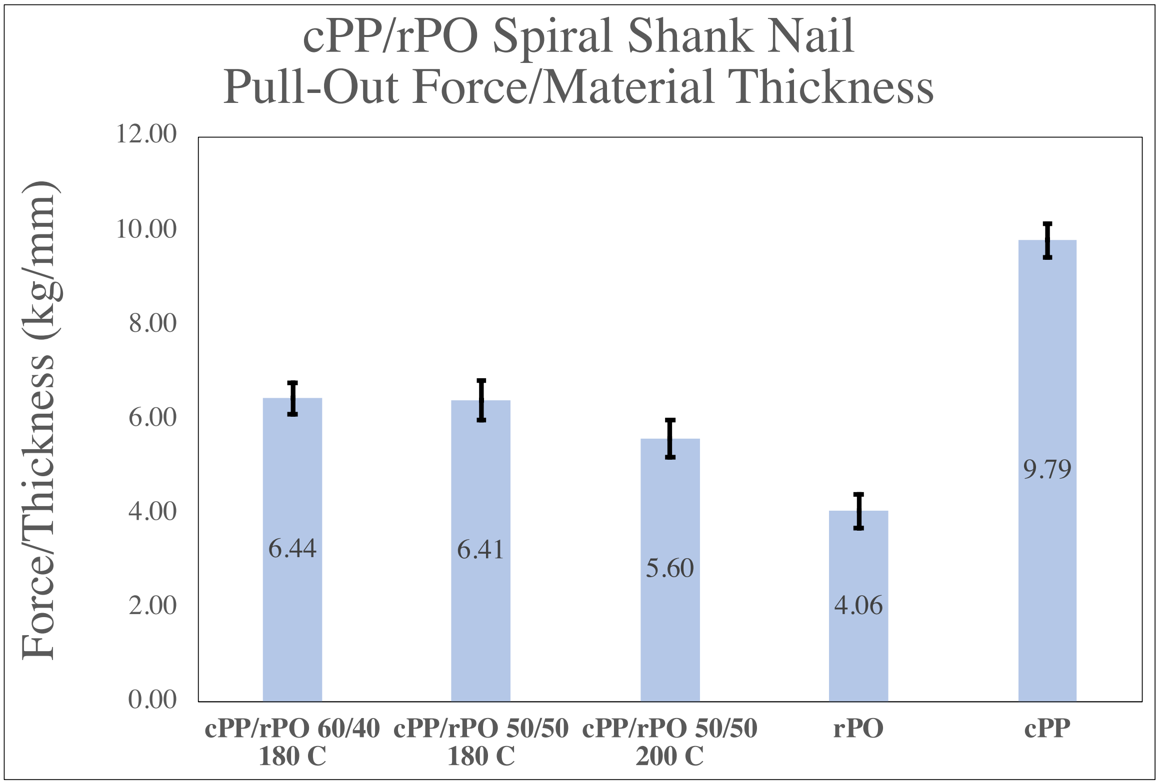

Figure 4.34: cPP/rPO spiral shank nail pull-out force/material thickness averages.

The cPP/rPO samples tested with spiral shank nails yielded an average pull-out resistance strength between cPP and rPO. For cPP/rPO samples, the 60/40 weight ratio compression molded at 180° C had the highest average pull-out resistance of 6.44 kg/mm, with the samples having a 50/50 weight ratio molded at 180° C just below at 6.41 kg/mm.

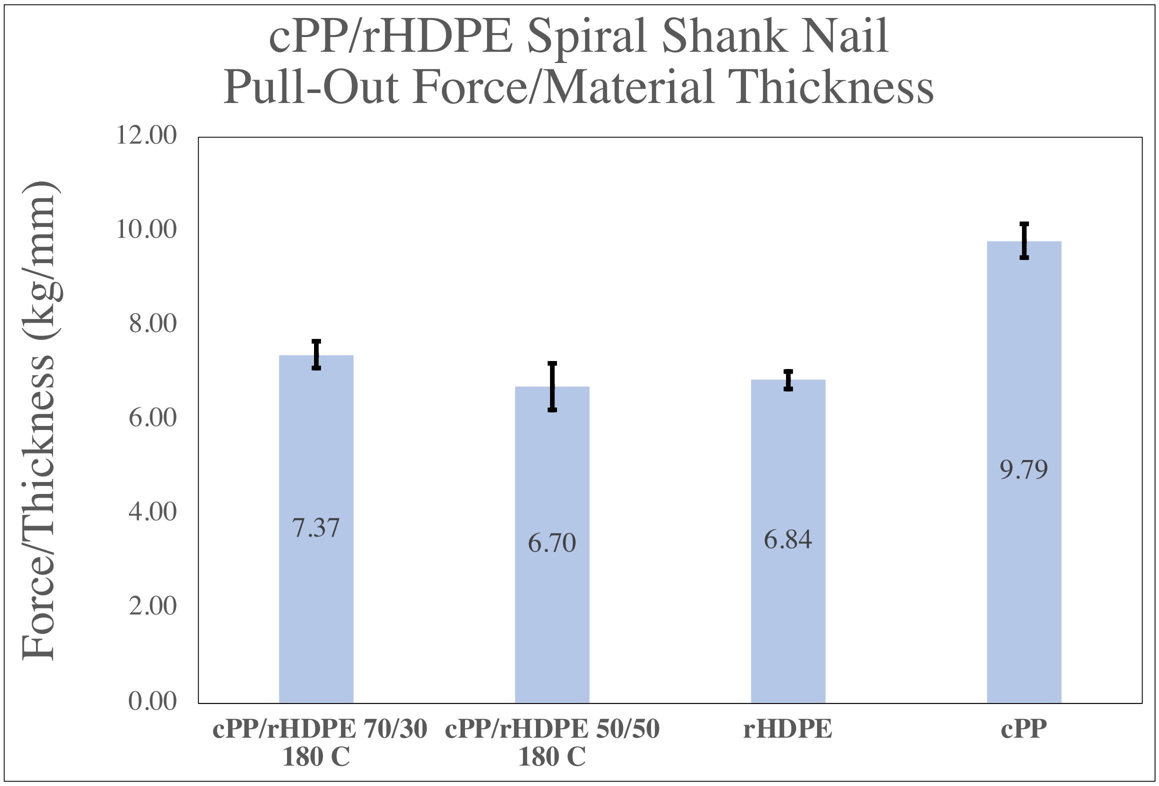

Figure 4.35: cPP/rHDPE spiral shank nail pull-out force/material thickness averages.

Out of the cPP/rHDPE samples tested with spiral shank nails, only the samples with a 70/30 mass ratio molded at 180° C had an average pull-out resistance strength between rHDPE and cPP. The cPP/rHDPE samples with a 50/50 mass ratio molded at 180° C had an average pull-out resistance strength lower than both rHDPE and cPP. Of the cPP/rHDPE samples, the samples with a 70/30 mass ratio molded at 180° C had the higher average pull-out resistance strength of the two composites at 7.37 kg/mm.

Table 4.14: Spiral shank nail pull-out force/fastener contact area averages.

Spiral Shank Nail Pull-Out Force/Fastener Contact Area			
Composition	**Force/Area (kg/mm^2)**	**95% Confidence Interval (+/-)**	**Standard Deviation**
Pine Wood	0.26	0.01	0.01
cPP/rPO 60/40 180 C	0.59	0.03	0.03
cPP/rPO 50/50 180 C	0.58	0.04	0.04
cPP/rPO 50/50 200 C	0.51	0.04	0.04
cPP/rHDPE 70/30 180 C	0.67	0.03	0.03
cPP/rHDPE 50/50 180 C	0.61	0.04	0.05
rHDPE	0.62	0.02	0.02
rPO	0.37	0.03	0.04
cPP	0.89	0.03	0.04

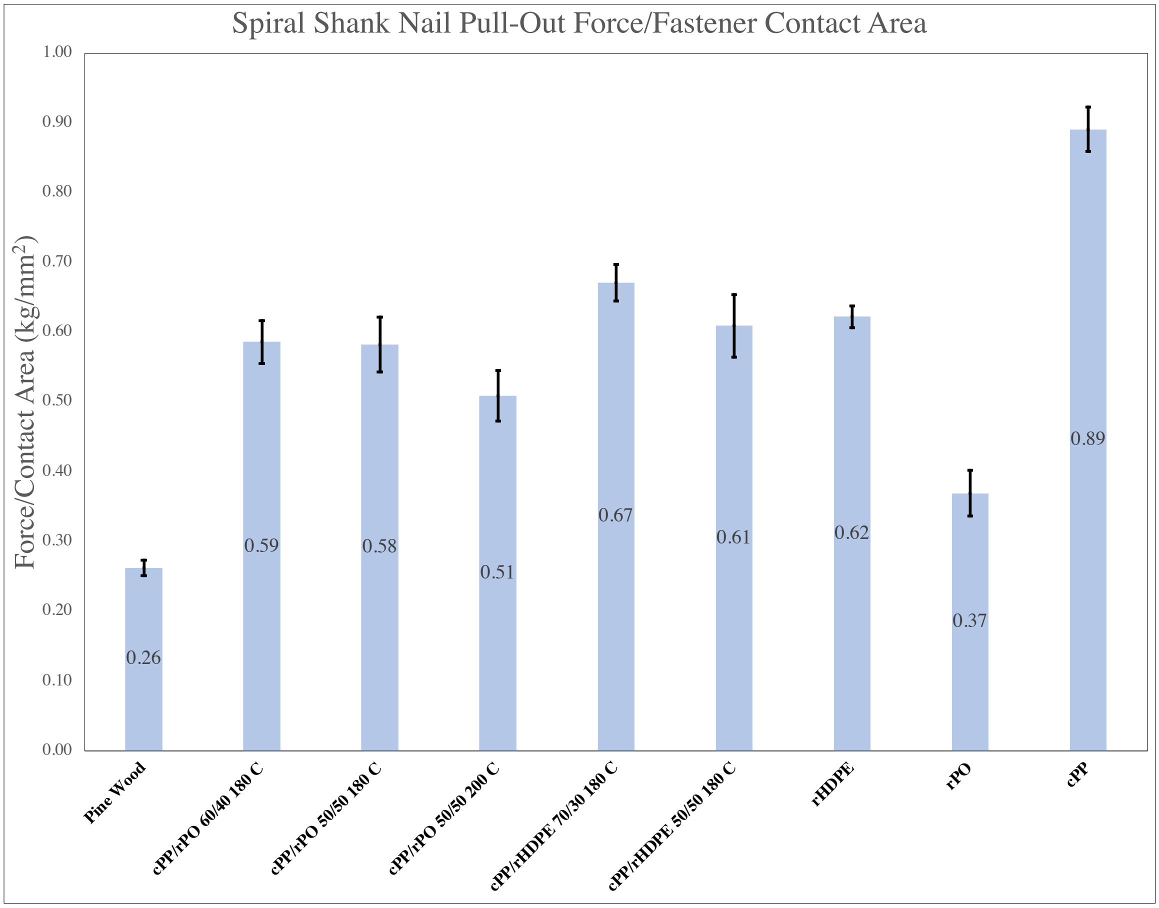

Figure 4.36: Spiral shank nail pull-out force/fastener contact area averages.

For spiral shank nails, all composite samples had greater pull-out resistances then pine wood.

4.4 Discussion:

Table 4.15: Pull-out force/material thickness summarized results.

Pull-Out Force/Material Thickness (kg/mm)							
	#8 Wood Screw	#12 Wood Screw	10-24 Bolt	5/16-18 Bolt	Common Nail	Ring Shank Nail	Spiral Shank Nail
Pine Wood	7.69	13.77	N/A	N/A	0.71	2.30	2.90
cPP/rPO 60/40 180 C	22.64	41.82	26.96	44.45	5.23	9.48	6.44
cPP/rPO 50/50 180 C	21.42	40.28	30.55	38.77	4.55	8.48	6.41
cPP/rPO 50/50 200 C	20.47	33.65	25.39	27.59	5.08	5.84	5.60
cPP/rHDPE 70/30 180 C	18.99	39.03	31.22	35.20	5.25	9.51	7.37
cPP/rHDPE 50/50 180 C	21.01	40.87	28.60	34.82	4.48	8.87	6.70
cPET/rPET	26.59	46.00	31.84	53.73	N/A	N/A	N/A
rHDPE	16.75	30.87	21.47	29.55	5.02	8.54	6.84
rPO	16.27	26.71	19.18	27.13	3.07	5.30	4.06
rPET	34.10	54.39	53.99	69.96	N/A	N/A	N/A
cPP	24.10	26.48	34.79	46.98	7.08	12.63	9.79
cPET	25.31	25.29	28.69	42.63	N/A	N/A	N/A

Table 4.16: Pull-out force/fastener contact area summarized results.

Pull-Out Force/Fastemer Contact Area (kg/mm^2)							
	#8 Wood Screw	#12 Wood Screw	10-24 Bolt	5/16-18 Bolt	Common Nail	Ring Shank Nail	Spiral Shank Nail
Pine Wood	0.59	0.79	N/A	N/A	0.08	0.23	0.31
cPP/rPO 60/40 180 C	1.73	2.40	1.79	1.81	0.54	0.97	0.59
cPP/rPO 50/50 180 C	1.64	2.31	2.03	1.58	0.48	0.86	0.58
cPP/rPO 50/50 200 C	1.56	1.93	1.69	1.12	0.55	0.61	0.51
cPP/rHDPE 70/30 180 C	1.45	2.24	2.08	1.43	0.57	0.96	0.67
cPP/rHDPE 50/50 180 C	1.61	2.35	1.90	1.42	0.48	0.90	0.61
cPET/rPET	2.03	2.64	2.12	2.19	N/A	N/A	N/A
rHDPE	1.28	1.77	1.43	1.20	0.54	0.86	0.62
rPO	1.24	1.53	1.28	1.10	0.33	0.54	0.37
rPET	2.61	3.12	3.59	2.85	N/A	N/A	N/A
cPP	1.84	1.52	2.31	1.91	0.76	1.66	1.06
cPET	1.93	1.45	1.91	1.74	N/A	N/A	N/A

The forces recorded in the pull-out tests were used to find the average pull-out force/material thickness and average pull-out force/fastener contact area values for each category of sample. The pull-out force/material thickness can be used to determine which material has the greatest pull-out resistance strength for a particular fastener. The pull-out force/fastener contact area can be used to determine the effectiveness of a fastener in each material.

For wood screws, the larger diameter #12 wood screws required substantially more force to withdrawal from all materials than the smaller #8 wood screws. This is because the threads of the #12 wood screws have a larger area of contact with the material resulting in more force being required to overcome the shear stress limits of the material.

For bolts, the larger 5/16-18 bolts required more force than the smaller 10-24 bolts to be pulled out of all materials. Again, this is due to the larger contact area between the fastener threads and the material requiring more force to overcome the shear stress limits of the material. From the data it can be seen that the 10-24 bolts have a greater holding force per contact area than the 5/16-18 bolts for most materials. This may be because the 10-24 bolts have more thread engagement thus more contact area with the material as there are more threads per inch on the 10-24 bolts than the 5/16-18 bolts.

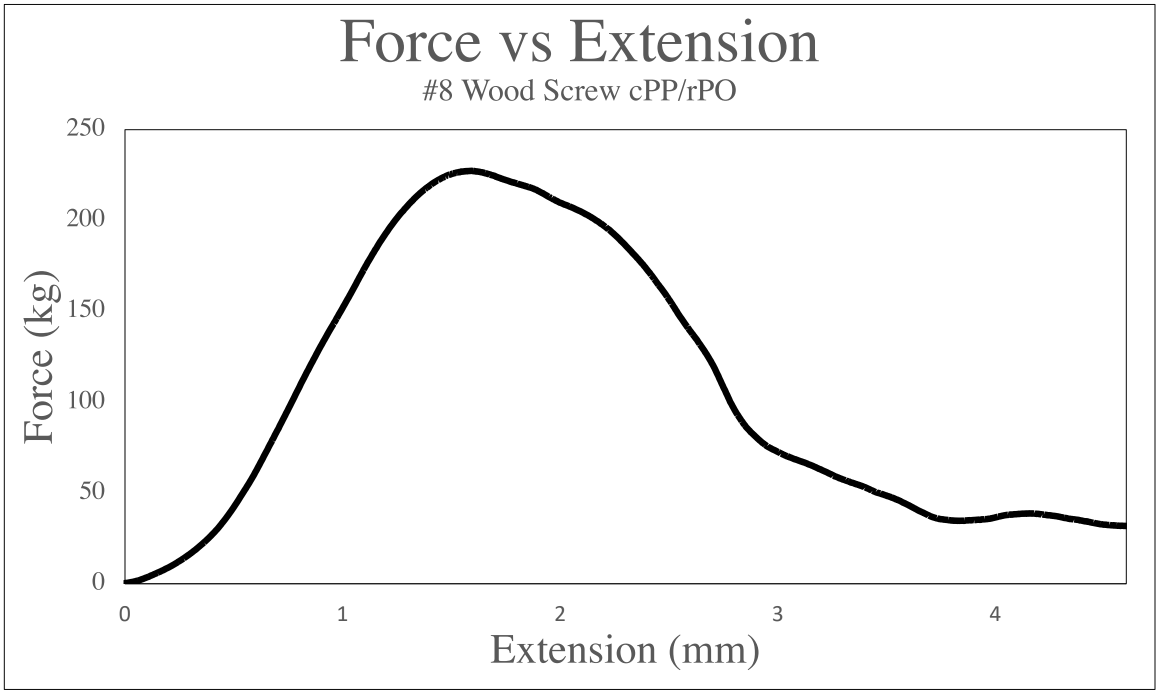

Figure 4.37: Force vs. extension curve of #8 wood screw in cPP/rPO demonstrating ductile failure.

All materials tested with threaded fasteners exhibited ductile failure during pull-out resistance tests. The force vs. extension curve in Figure 4.37 was typical of all combinations of threaded fasteners and materials tested. Plastic deformation of the material begins as the amount of force being applied to the threaded fastener grows until the shear stress limit of the material is reached and enough deformation has occurred that the amount of force required to pull the fastener can begin to decrease until it is fully removed from the material. Plastic deformation of cPET/rPET composite from screw withdrawal can be seen in Figure 4.38.

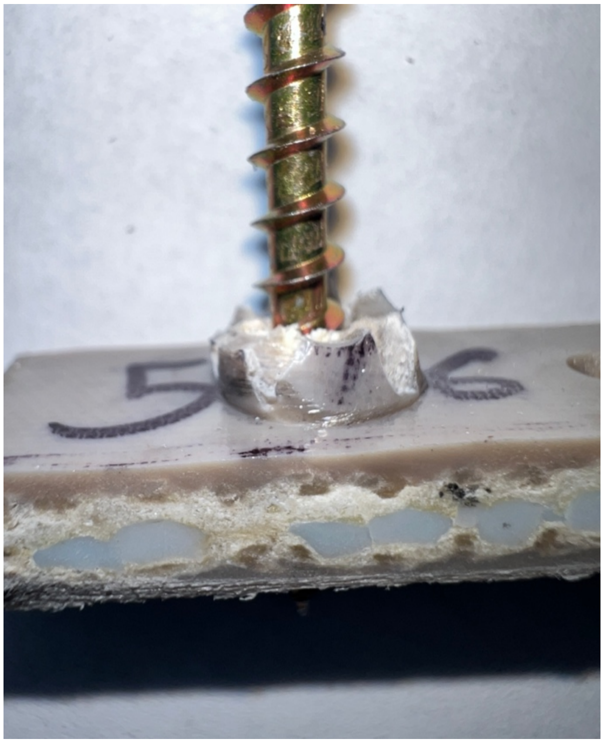

Figure 4.38: cPET/rPET with screw partially withdrawn from material.

The mode of failure for all threaded fastener pull-out tests was the upward force applied to the fastener causing the material to shear around the fastener threads.

The mode of failure for all the nail pull-out tests was the upward force overcoming the friction force gripping the shaft of the nail causing it to slide through the material. In Figure 4.39 the force vs. extension curve from a ring shank nailed being pulled out of a cPP/rPO sample demonstrates ductile failure as the pull-out force overcomes the friction force of the material holding the screw.

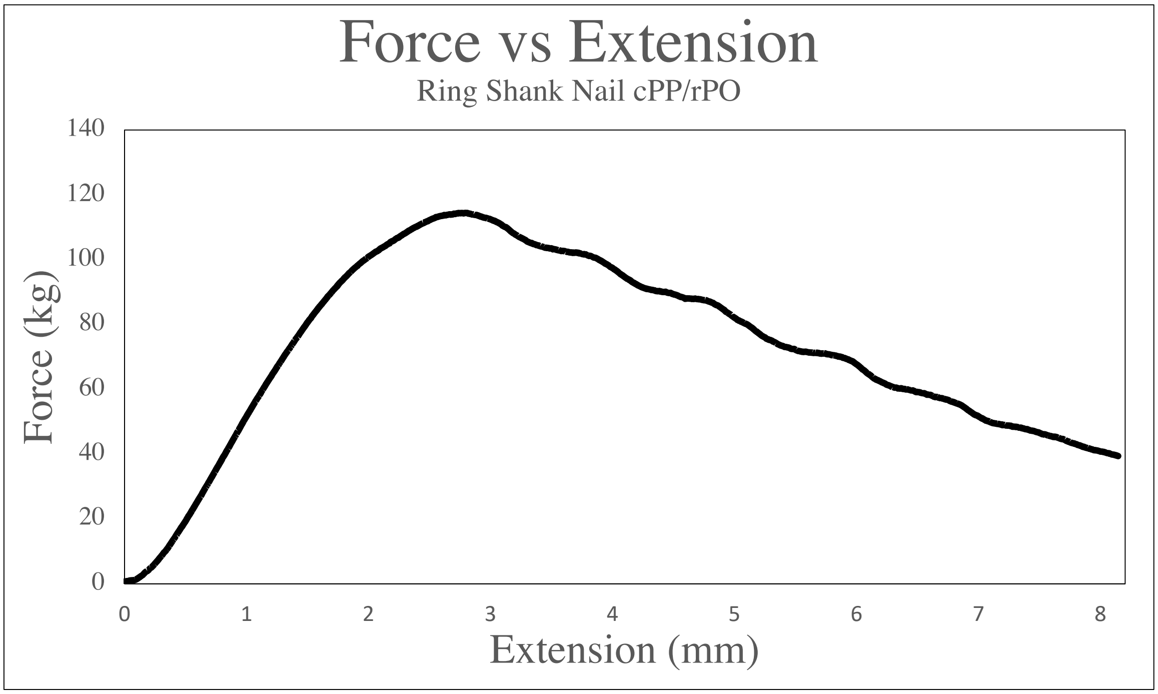

Figure 4.39: Force vs. extension curve of ring shank nail in cPP/rPO.

The nail and screw pull-out resistance strengths measured for pine wood in this study were consistent with pull-out strengths published by Aytekin in *Determination of Screw and Nail Withdrawal Resistance of Some Important Wood Species* [49].

Overall, the composite materials had greater fastener pull-out resistances than pine wood, the most common material in forklift pallet construction. The data collected in this study shows how composite materials made from recycled carpet and polymer pellets could be used in light structural applications.

CHAPTER V

CONCLUSIONS

Fastener pull-out resistance tests were conducted on composites made from post-consumer carpet materials and pellets made from recycled polymer materials. The composites made from recycled materials were fabricated through compression molding using custom three-piece molds. Screws, bolts, and nails were used to test the fastener pull-out resistance of the recycled polymer composites. Fasteners were inserted at a right angle into the face of the materials and pulled out using a custom fixture attached to an Instron universal testing machine.

The screw and nail pull-out resistance of the composite materials was compared against the screw and nail pull-out resistance of pine wood, samples made of carpet only, and samples made from resin only. Samples made of carpet only and recycled polymer only were fabricated using the same compression molding methods and parameters used to make the recycled composite materials.

It was found that all the recycled composite materials have greater pull-out resistance with screws than pine wood. The cPP/rPO and cPP/rHDPE composites have greater pull-out resistance with nails than pine wood. Composites made with rPET were not able to have the pull-out resistance tested with nails as they would crack and break upon driving a nail into the material. This is because PET is very brittle, much more than PO and HDPE.

In this study, it was also shown that holes can be drilled into the face of the composite materials and threads cut into the holes to mate with bolts. The pull-out force per fastener contact area for the bolts tested had some of the largest values of all the material/fastener combinations. The high pull-out force per fastener contact area allow for a strong clamping force to be applied to the material with a bolt. This finding has the potential for a wider variety of uses to be found for the recycled carpet composite materials. Many of the materials commonly used in light structural applications such as wood, PB, fiberboard, plywood, MDF, and OBF do not have the ability for threads to be cut in the material and used with bolts. Threaded holes with bolts allow for repeated non-destructive removal, something that cannot be done with screws or nails.

Both cPP and cPET only samples showed very good fastener pull-out resistance in this study. In many instances the pull-out resistance of cPP was stronger than the composites made using cPP with rHDPE or rPO. For future investigation, samples with more layers of carpet should be molded to produce thicker samples capable of supporting more weight and higher forces. One of the main objectives of this project was to recycle post-consumer waste carpet by transforming it into a new and useful material. More carpet per unit mass of material produced would be recycled compared to the materials made using carpet and recycled polymer pellets. Also. the potential for a strong material to be compression molded with only carpet would simplify the manufacturing process and reduce costs.

The thickness of the composite samples may be a limitation to the accuracy of the results. The samples were made using two layer of carpet that when compressed during molding would produce samples that were only a few millimeters thick which highly limited the amount of fastener engagement. To improve the accuracy of the test results thicker samples are needed to increase the amount of fastener engagement with the material. Making samples with more layers of carpet and resin would increase the thickness of the composite materials. Also, testing could be done on multiple composite samples stacked on top of each other and driving a fastener through the multiple layers to increase the amount of fastener engagement. Another way to improve the accuracy of this study's results would be to increase sample size of all the materials tested.

Areas for future study with recycled composite materials include conducting tests on lap joints bonded with fasteners, testing samples that have been weathered, and improving the interface between the carpet and resin. To better understand the fastener retention properties of these materials more sizes of fasteners should be tested.

From the results of this study, it can be determined that compression molded recycled polymer composite have excellent fastener retention properties. This is an important property for the recycled composite materials to find use in light structural applications. By being able to convert post-consumer carpet waste into useful composite materials new value is given to a product that is otherwise difficult to recycle and is often sent to take up space in landfills. By saving carpet waste from ending up in landfills the negative environmental impacts of this material is greatly reduced helping to make the world a cleaner and more sustainable place.

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APPENDICES

This is the data collected from all the fastener pull-out tests.

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)	Pilot Hole	Pilot Hole
cPP/rPO 50/50 180 C								
439	cPP/rPO 50/50 180 C	11.58	#8 Wood Screw	275	23.75	1.8149	9/64 in	3.572 mm
454	cPP/rPO 50/50 180 C	11.65	#8 Wood Screw	270	23.18	1.7712	9/64 in	3.572 mm
482	cPP/rPO 50/50 180 C	11.45	#8 Wood Screw	230	20.09	1.5352	9/64 in	3.572 mm
439	cPP/rPO 50/50 180 C	11.58	#8 Wood Screw	260	22.45	1.7159	9/64 in	3.572 mm
439	cPP/rPO 50/50 180 C	11.58	#8 Wood Screw	265	22.88	1.7489	9/64 in	3.572 mm
454	cPP/rPO 50/50 180 C	11.65	#8 Wood Screw	240	20.60	1.5744	9/64 in	3.572 mm
454	cPP/rPO 50/50 180 C	11.65	#8 Wood Screw	260	22.32	1.7056	9/64 in	3.572 mm
482	cPP/rPO 50/50 180 C	11.45	#8 Wood Screw	215	18.78	1.4351	9/64 in	3.572 mm
482	cPP/rPO 50/50 180 C	11.45	#8 Wood Screw	215	18.78	1.4351	9/64 in	3.572 mm
cPP/rPO 50/50 200 C								
456	cPP/rPO 50/50 200 C	11.12	#8 Wood Screw	235	21.13	1.6151	9/64 in	3.572 mm
457	cPP/rPO 50/50 200 C	11.58	#8 Wood Screw	230	19.86	1.5179	9/64 in	3.572 mm
483	cPP/rPO 50/50 200 C	11.04	#8 Wood Screw	220	19.93	1.5230	9/64 in	3.572 mm
456	cPP/rPO 50/50 200 C	11.12	#8 Wood Screw	240	21.58	1.6495	9/64 in	3.572 mm
456	cPP/rPO 50/50 200 C	11.12	#8 Wood Screw	255	22.93	1.7526	9/64 in	3.572 mm
457	cPP/rPO 50/50 200 C	11.58	#8 Wood Screw	205	17.70	1.3529	9/64 in	3.572 mm
457	cPP/rPO 50/50 200 C	11.58	#8 Wood Screw	225	19.43	1.4849	9/64 in	3.572 mm
483	cPP/rPO 50/50 200 C	11.04	#8 Wood Screw	250	22.64	1.7306	9/64 in	3.572 mm
483	cPP/rPO 50/50 200 C	11.04	#8 Wood Screw	210	19.02	1.4537	9/64 in	3.572 mm
cPPrPO 60/40 180 C								
514	cPPrPO 60/40 180 C	9.61	#8 Wood Screw	258	26.85	2.0518	9/64 in	3.572 mm
496	cPPrPO 60/40 180 C	9.41	#8 Wood Screw	199	21.15	1.6162	9/64 in	3.572 mm
500	cPPrPO 60/40 180 C	9.55	#8 Wood Screw	217	22.72	1.7366	9/64 in	3.572 mm
500	cPPrPO 60/40 180 C	9.55	#8 Wood Screw	207	21.68	1.6565	9/64 in	3.572 mm
514	cPPrPO 60/40 180 C	9.61	#8 Wood Screw	200	20.81	1.5905	9/64 in	3.572 mm
cPP/rHDPE 70/30 180 C								
497i	cPP/rHDPE 70/30 180 C	8.12	#8 Wood Screw	165	20.32	1.5530	9/64 in	3.572 mm
487i	cPP/rHDPE 70/30 180 C	8.17	#8 Wood Screw	170	20.81	1.5902	9/64 in	3.572 mm
487ii	cPP/rHDPE 70/30 180 C	8.29	#8 Wood Screw	145	17.49	1.3367	9/64 in	3.572 mm
487i	cPP/rHDPE 70/30 180 C	8.17	#8 Wood Screw	155	18.97	1.4499	9/64 in	3.572 mm
487i	cPP/rHDPE 70/30 180 C	8.17	#8 Wood Screw	160	19.58	1.4967	9/64 in	3.572 mm
487ii	cPP/rHDPE 70/30 180 C	8.29	#8 Wood Screw	160	19.30	1.4750	9/64 in	3.572 mm
487ii	cPP/rHDPE 70/30 180 C	8.29	#8 Wood Screw	160	19.30	1.4750	9/64 in	3.572 mm
497i	cPP/rHDPE 70/30 180 C	8.12	#8 Wood Screw	155	19.09	1.4589	9/64 in	3.572 mm
497i	cPP/rHDPE 70/30 180 C	8.12	#8 Wood Screw	130	16.01	1.2236	9/64 in	3.572 mm
cPP/rHDPE 50/50 180 C								
501i	cPP/rHDPE 50/50 180 C	11.57	#8 Wood Screw	255	22.04	1.6844	9/64 in	3.572 mm
501ii	cPP/rHDPE 50/50 180 C	11.45	#8 Wood Screw	255	22.27	1.7020	9/64 in	3.572 mm
501i	cPP/rHDPE 50/50 180 C	11.57	#8 Wood Screw	220	19.01	1.4532	9/64 in	3.572 mm
501i	cPP/rHDPE 50/50 180 C	11.57	#8 Wood Screw	240	20.74	1.5853	9/64 in	3.572 mm
501ii	cPP/rHDPE 50/50 180 C	11.45	#8 Wood Screw	240	20.96	1.6019	9/64 in	3.572 mm
501ii	cPP/rHDPE 50/50 180 C	11.45	#8 Wood Screw	240	20.96	1.6019	9/64 in	3.572 mm
cPET								
649	cPET	4.34	#8 Wood Screw	113	26.04	1.9899	9/64 in	3.572 mm
649	cPET	4.34	#8 Wood Screw	107	24.65	1.8842	9/64 in	3.572 mm
643	cPET	4.47	#8 Wood Screw	99	22.15	1.6926	9/64 in	3.572 mm
643	cPET	4.47	#8 Wood Screw	120	26.85	2.0517	9/64 in	3.572 mm
654	cPET	4.47	#8 Wood Screw	120	26.85	2.0517	9/64 in	3.572 mm
654	cPET	4.47	#8 Wood Screw	127	28.41	2.1714	9/64 in	3.572 mm

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)	Pilot Hole	Pilot Hole
cPET/rPET								
638	cPET/rPET	6.10	#8 Wood Screw	171	28.03	2.1424	9/64 in	3.572 mm
634	cPET/rPET	6.04	#8 Wood Screw	178	29.47	2.2523	9/64 in	3.572 mm
634	cPET/rPET	6.04	#8 Wood Screw	150	24.83	1.8980	9/64 in	3.572 mm
634	cPET/rPET	6.04	#8 Wood Screw	150	24.83	1.8980	9/64 in	3.572 mm
640	cPET/rPET	6.06	#8 Wood Screw	190	31.35	2.3962	9/64 in	3.572 mm
640	cPET/rPET	6.06	#8 Wood Screw	142	23.43	1.7908	9/64 in	3.572 mm
636	cPET/rPET	6.42	#8 Wood Screw	170	26.48	2.0237	9/64 in	3.572 mm
636	cPET/rPET	6.42	#8 Wood Screw	156	24.30	1.8571	9/64 in	3.572 mm
rPET								
657	rPET	4.54	#8 Wood Screw	140	30.84	2.3567	9/64 in	3.572 mm
664	rPET	4.51	#8 Wood Screw	181	40.13	3.0672	9/64 in	3.572 mm
664	rPET	4.51	#8 Wood Screw	164	36.36	2.7791	9/64 in	3.572 mm
656	rPET	5.05	#8 Wood Screw	141	27.92	2.1338	9/64 in	3.572 mm
662	rPET	4.88	#8 Wood Screw	172	35.25	2.6937	9/64 in	3.572 mm
659	rPET	4.66	#8 Wood Screw	180	38.63	2.9520	9/64 in	3.572 mm
HDPE								
646	rHDPE	11.62	#8 Wood Screw	193	16.61	1.2694	9/64 in	3.572 mm
646	rHDPE	11.62	#8 Wood Screw	180	15.49	1.1839	9/64 in	3.572 mm
646	rHDPE	11.62	#8 Wood Screw	191	16.44	1.2562	9/64 in	3.572 mm
481	rHDPE	5.88	#8 Wood Screw	107	18.20	1.3907	9/64 in	3.572 mm
481	rHDPE	5.88	#8 Wood Screw	100	17.01	1.2997	9/64 in	3.572 mm
Pine Wood								
1	Pine Wood	13.24	#8 Wood Screw	105	7.93	0.6061	7/64 in	2.778 mm
1	Pine Wood	10.88	#8 Wood Screw	100	9.19	0.7024	7/64 in	2.778 mm
1	Pine Wood	10.88	#8 Wood Screw	75	6.89	0.5268	7/64 in	2.778 mm
1	Pine Wood	13.47	#8 Wood Screw	95	7.05	0.5390	7/64 in	2.778 mm
1	Pine Wood	13.24	#8 Wood Screw	98	7.40	0.5657	7/64 in	2.778 mm
rPO								
543	rPO	11.97	#8 Wood Screw	214	17.88	1.3663	9/64 in	3.572 mm
543	rPO	11.97	#8 Wood Screw	190	15.87	1.2131	9/64 in	3.572 mm
543	rPO	11.97	#8 Wood Screw	181	15.12	1.1556	9/64 in	3.572 mm
543	rPO	11.97	#8 Wood Screw	184	15.37	1.1748	9/64 in	3.572 mm
543	rPO	11.97	#8 Wood Screw	205	17.13	1.3089	9/64 in	3.572 mm
cPP								
402	cPP	5.61	#8 Wood Screw	133	23.71	1.8119	9/64 in	3.572 mm
436	cPP	5.24	#8 Wood Screw	120	22.90	1.7502	9/64 in	3.572 mm
432	cPP	5.47	#8 Wood Screw	139	25.41	1.9421	9/64 in	3.572 mm
402	cPP	5.61	#8 Wood Screw	135	24.06	1.8391	9/64 in	3.572 mm
436	cPP	5.24	#8 Wood Screw	128	24.43	1.8669	9/64 in	3.572 mm
cPP/rPO 60/40 180 C								
514	cPP/rPO 60/40 180 C	9.64	#12 Wood Screw	368	38.17	2.19	11/64 in	4.36563 mm
500	cPP/rPO 60/40 180 C	9.82	#12 Wood Screw	401	40.84	2.34	11/64 in	4.36563 mm
496	cPP/rPO 60/40 180 C	9.34	#12 Wood Screw	418	44.75	2.56	11/64 in	4.36563 mm
514	cPP/rPO 60/40 180 C	9.64	#12 Wood Screw	423	43.88	2.51	11/64 in	4.36563 mm
500	cPP/rPO 60/40 180 C	9.82	#12 Wood Screw	407	41.45	2.37	11/64 in	4.36563 mm
cPP/rPO 50/50 180 C								
459	cPP/rPO 50/50 180 C	11.54	#12 Wood Screw	490	42.46	2.43	11/64 in	4.36563 mm
482	cPP/rPO 50/50 180 C	11.55	#12 Wood Screw	459	39.74	2.28	11/64 in	4.36563 mm
481	cPP/rPO 50/50 180 C	10.81	#12 Wood Screw	434	40.15	2.30	11/64 in	4.36563 mm
439	cPP/rPO 50/50 180 C	11.64	#12 Wood Screw	456	39.18	2.24	11/64 in	4.36563 mm
440	cPP/rPO 50/50 180 C	11.53	#12 Wood Screw	460	39.90	2.29	11/64 in	4.36563 mm
cPP/rPO 50/50 200 C								
462	cPP/rPO 50/50 200 C	11.51	#12 Wood Screw	387	33.62	1.93	11/64 in	4.36563 mm
450	cPP/rPO 50/50 200 C	10.76	#12 Wood Screw	347	32.25	1.85	11/64 in	4.36563 mm
483	cPP/rPO 50/50 200 C	11.01	#12 Wood Screw	407	36.97	2.12	11/64 in	4.36563 mm
457	cPP/rPO 50/50 200 C	11.27	#12 Wood Screw	368	32.65	1.87	11/64 in	4.36563 mm
456	cPP/rPO 50/50 200 C	11.15	#12 Wood Screw	365	32.74	1.88	11/64 in	4.36563 mm

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)	Pilot Hole	Pilot Hole
cPP/rHDPE 70/30 180 C								
497	cPP/rHDPE 70/30 180 C	8.12	#12 Wood Screw	334	41.13	2.36	11/64 in	4.36563 mm
487	cPP/rHDPE 70/30 180 C	8.17	#12 Wood Screw	294	35.99	2.06	11/64 in	4.36563 mm
515	cPP/rHDPE 70/30 180 C	8.19	#12 Wood Screw	334	40.78	2.34	11/64 in	4.36563 mm
515	cPP/rHDPE 70/30 180 C	8.19	#12 Wood Screw	317	38.71	2.22	11/64 in	4.36563 mm
497	cPP/rHDPE 70/30 180 C	8.12	#12 Wood Screw	313	38.55	2.21	11/64 in	4.36563 mm
cPP/rHDPE 50/50 180 C								
510	cPP/rHDPE 50/50 180 C	11.27	#12 Wood Screw	468	41.53	2.38	11/64 in	4.36563 mm
501	cPP/rHDPE 50/50 180 C	11.46	#12 Wood Screw	462	40.31	2.31	11/64 in	4.36563 mm
510	cPP/rHDPE 50/50 180 C	11.27	#12 Wood Screw	459	40.73	2.33	11/64 in	4.36563 mm
501	cPP/rHDPE 50/50 180 C	11.46	#12 Wood Screw	472	41.19	2.36	11/64 in	4.36563 mm
510	cPP/rHDPE 50/50 180 C	11.27	#12 Wood Screw	465	40.58	2.36	11/64 in	4.36563 mm
cPET/rPET								
637	cPET/rPET	5.67	#12 Wood Screw	317	55.91	3.20	11/64 in	4.36563 mm
631	cPET/rPET	6.41	#12 Wood Screw	297	46.33	2.65	11/64 in	4.36563 mm
641	cPET/rPET	6.38	#12 Wood Screw	248	38.87	2.23	11/64 in	4.36563 mm
634	cPET/rPET	5.97	#12 Wood Screw	224	37.52	2.15	11/64 in	4.36563 mm
631	cPET/rPET	6.43	#12 Wood Screw	305	47.43	2.72	11/64 in	4.36563 mm
634	cPET/rPET	5.97	#12 Wood Screw	298	49.92	2.86	11/64 in	4.36563 mm
rHDPE								
481	rHDPE	5.83	#12 Wood Screw	175	30.02	1.72	11/64 in	4.36563 mm
481	rHDPE	5.83	#12 Wood Screw	171	29.33	1.68	11/64 in	4.36563 mm
481	rHDPE	5.83	#12 Wood Screw	186	31.90	1.83	11/64 in	4.36563 mm
481	rHDPE	5.83	#12 Wood Screw	186	31.90	1.83	11/64 in	4.36563 mm
481	rHDPE	5.83	#12 Wood Screw	182	31.22	1.79	11/64 in	4.36563 mm
rPO								
543	rPO	11.97	#12 Wood Screw	318	26.57	1.52	11/64 in	4.36563 mm
543	rPO	11.97	#12 Wood Screw	330	27.57	1.58	11/64 in	4.36563 mm
543	rPO	11.97	#12 Wood Screw	322	26.90	1.54	11/64 in	4.36563 mm
543	rPO	11.97	#12 Wood Screw	299	24.98	1.43	11/64 in	4.36563 mm
543	rPO	11.97	#12 Wood Screw	331	27.65	1.58	11/64 in	4.36563 mm
543	rPO	11.97	#12 Wood Screw	318	26.57	1.52	11/64 in	4.36563 mm
rPET								
664	rPET	5.06	#12 Wood Screw	311	61.46	3.52	11/64 in	4.36563 mm
663	rPET	4.95	#12 Wood Screw	253	51.11	2.93	11/64 in	4.36563 mm
661	rPET	4.79	#12 Wood Screw	260	54.28	3.11	11/64 in	4.36563 mm
630	rPET	4.52	#12 Wood Screw	237	52.43	3.00	11/64 in	4.36563 mm
659	rPET	4.99	#12 Wood Screw	332	66.53	3.81	11/64 in	4.36563 mm
658	rPET	4.61	#12 Wood Screw	227	49.24	2.82	11/64 in	4.36563 mm
660	rPET	4.84	#12 Wood Screw	221	45.66	2.62	11/64 in	4.36563 mm
cPET								
653	cPET	4.06	#12 Wood Screw	115	28.33	1.62	11/64 in	4.36563 mm
649	cPET	4.19	#12 Wood Screw	115	27.45	1.57	11/64 in	4.36563 mm
638	cPET	5.8	#12 Wood Screw	124	21.38	1.22	11/64 in	4.36563 mm
648	cPET	4.1	#12 Wood Screw	102	24.88	1.43	11/64 in	4.36563 mm
650	cPET	4.3	#12 Wood Screw	105	24.42	1.40	11/64 in	4.36563 mm
cPP								
543	PO 100	11.97	#12 Wood Screw	324	27.07	1.55	11/64 in	4.36563 mm
543	PO 100	11.97	#12 Wood Screw	313	26.15	1.50	11/64 in	4.36563 mm
543	PO 100	11.97	#12 Wood Screw	308	25.73	1.47	11/64 in	4.36563 mm
543	PO 100	11.97	#12 Wood Screw	314	26.23	1.50	11/64 in	4.36563 mm
543	PO 100	11.97	#12 Wood Screw	326	27.23	1.56	11/64 in	4.36563 mm

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)	Pilot Hole	Pilot Hole
Pine Wood								
1	Pine Wood	24.51	#12 Wood Screw	429	17.50	1.00	9/64 in	3.57187 mm
1	Pine Wood	34.79	#12 Wood Screw	580	16.67	0.96	9/64 in	3.57187 mm
1	Pine Wood	17.56	#12 Wood Screw	197	11.22	0.64	9/64 in	3.57187 mm
1	Pine Wood	17.56	#12 Wood Screw	209	11.90	0.68	9/64 in	3.57187 mm
1	Pine Wood	17.56	#12 Wood Screw	203	11.56	0.66	9/64 in	3.57187 mm

cPP/rPO 50/50 180 C								
482	cPP/rPO 50/50 180 C	11.54	10-24 bolt	338	29.29	1.95	#25 drill bit	3.79 mm
482	cPP/rPO 50/50 180 C	11.54	10-24 bolt	359	31.11	2.07	#25 drill bit	3.79 mm
454	cPP/rPO 50/50 180 C	11.85	10-24 bolt	342	28.86	1.92	#25 drill bit	3.79 mm
454	cPP/rPO 50/50 180 C	11.85	10-24 bolt	364	30.72	2.04	#25 drill bit	3.79 mm
482	cPP/rPO 50/50 180 C	11.54	10-24 bolt	378	32.76	2.18	#25 drill bit	3.79 mm

cPP/rPO 50/50 200 C								
450	cPP/rPO 50/50 200 C	11.10	10-24 bolt	290	26.13	1.74	#25 drill bit	3.79 mm
462	cPP/rPO 50/50 200 C	11.49	10-24 bolt	308	26.81	1.78	#25 drill bit	3.79 mm
462	cPP/rPO 50/50 200 C	11.49	10-24 bolt	265	23.06	1.53	#25 drill bit	3.79 mm
462	cPP/rPO 50/50 200 C	11.49	10-24 bolt	291	25.33	1.68	#25 drill bit	3.79 mm
483	cPP/rPO 50/50 200 C	11.01	10-24 bolt	282	25.61	1.70	#25 drill bit	3.79 mm

cPP/rPO 60/40 180 C								
500	cPP/rPO 60/40 180 C	9.78	10-24 bolt	330	33.74	2.24	#25 drill bit	3.79 mm
500	cPP/rPO 60/40 180 C	10.78	10-24 bolt	307	28.48	1.89	#25 drill bit	3.79 mm
500	cPP/rPO 60/40 180 C	12.78	10-24 bolt	271	21.21	1.41	#25 drill bit	3.79 mm
500	cPP/rPO 60/40 180 C	13.78	10-24 bolt	294	21.34	1.42	#25 drill bit	3.79 mm
496	cPP/rPO 60/40 180 C	9.56	10-24 bolt	287	30.02	2.00	#25 drill bit	3.79 mm

cPP/rHDPE 50/50 180 C								
501	cPP/rHDPE 50/50 180 C	11.54	10-24 bolt	307	26.60	1.77	#25 drill bit	3.79 mm
501	cPP/rHDPE 50/50 180 C	11.54	10-24 bolt	349	30.24	2.01	#25 drill bit	3.79 mm
510	cPP/rHDPE 50/50 180 C	11.20	10-24 bolt	305	27.23	1.81	#25 drill bit	3.79 mm
501	cPP/rHDPE 50/50 180 C	11.54	10-24 bolt	342	29.64	1.97	#25 drill bit	3.79 mm
510	cPP/rHDPE 50/50 180 C	11.20	10-24 bolt	328	29.29	1.95	#25 drill bit	3.79 mm

cPP/rHDPE 70/30 180 C								
487	cPP/rHDPE 70/30 180 C	8.30	10-24 bolt	238	28.67	1.91	#25 drill bit	3.79 mm
515	cPP/rHDPE 70/30 180 C	8.19	10-24 bolt	265	32.36	2.15	#25 drill bit	3.79 mm
487	cPP/rHDPE 70/30 180 C	8.30	10-24 bolt	255	30.72	2.04	#25 drill bit	3.79 mm
515	cPP/rHDPE 70/30 180 C	8.19	10-24 bolt	262	31.99	2.13	#25 drill bit	3.79 mm
515	cPP/rHDPE 70/30 180 C	8.19	10-24 bolt	265	32.36	2.15	#25 drill bit	3.79 mm

cPET								
654	cPET	4.36	10-24 bolt	113	25.92	1.72	#25 drill bit	3.79 mm
645	cPET	4.56	10-24 bolt	131	28.73	1.91	#25 drill bit	3.79 mm
645	cPET	4.07	10-24 bolt	135	33.17	2.21	#25 drill bit	3.79 mm
643	cPET	4.47	10-24 bolt	124	27.74	1.85	#25 drill bit	3.79 mm
654	cPET	4.23	10-24 bolt	118	27.90	1.86	#25 drill bit	3.79 mm

rPET								
659	rPET	4.75	10-24 bolt	251	52.84	3.51	#25 drill bit	3.79 mm
663	rPET	5.08	10-24 bolt	278	54.72	3.64	#25 drill bit	3.79 mm
659	rPET	4.85	10-24 bolt	250	51.55	3.43	#25 drill bit	3.79 mm
636	rPET	4.93	10-24 bolt	276	55.98	3.72	#25 drill bit	3.79 mm
656	rPET	4.45	10-24 bolt	244	54.83	3.65	#25 drill bit	3.79 mm

cPET/rPET								
639	cPET/rPET	6.51	10-24 bolt	232	35.64	2.37	#25 drill bit	3.79 mm
641	cPET/rPET	6.19	10-24 bolt	234	37.80	2.51	#25 drill bit	3.79 mm
639	cPET/rPET	6.44	10-24 bolt	181	28.11	1.87	#25 drill bit	3.79 mm
632	cPET/rPET	6.19	10-24 bolt	185	29.89	1.99	#25 drill bit	3.79 mm
635	cPET/rPET	6.30	10-24 bolt	175	27.78	1.85	#25 drill bit	3.79 mm
641	cPET/rPET	6.19	10-24 bolt	235	37.96	2.53	#25 drill bit	3.79 mm

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)	Pilot Hole	Pilot Hole
rHDPE								
464	rHDPE	11.70	10-24 bolt	265	22.65	1.51	#25 drill bit	3.79 mm
464	rHDPE	11.70	10-24 bolt	255	21.79	1.45	#25 drill bit	3.79 mm
464	rHDPE	11.70	10-24 bolt	241	20.60	1.37	#25 drill bit	3.79 mm
464	rHDPE	11.70	10-24 bolt	262	22.39	1.49	#25 drill bit	3.79 mm
464	rHDPE	11.70	10-24 bolt	233	19.91	1.32	#25 drill bit	3.79 mm

rPO								
543	rPO	11.97	10-24	233	19.47	1.29	#25 drill bit	3.79 mm
543	rPO	11.97	10-25	236	19.72	1.31	#25 drill bit	3.79 mm
543	rPO	11.97	10-26	227	18.96	1.26	#25 drill bit	3.79 mm
543	rPO	11.97	10-27	228	19.05	1.27	#25 drill bit	3.79 mm
543	rPO	11.97	10-28	224	18.71	1.24	#25 drill bit	3.79 mm

cPP								
402	cPP	5.61	10-24	192	34.22	2.28	#25 drill bit	3.79 mm
432	cPP	5.47	10-25	176	32.18	2.14	#25 drill bit	3.79 mm
436	cPP	5.24	10-26	198	37.79	2.51	#25 drill bit	3.79 mm
402	cPP	5.61	10-27	189	33.69	2.24	#25 drill bit	3.79 mm
436	cPP	5.24	10-28	189	36.07	2.40	#25 drill bit	3.79 mm

cPP/rPO 50/50 200 C								
457i	cPP/rPO 50/50 200 C	11.36	5/16-18 Bolt	355	31.25	1.27	F Drill Bit	6.50 mm
483ii	cPP/rPO 50/50 200 C	11.20	5/16-18 Bolt	300	26.79	1.09	F Drill Bit	6.50 mm
483i	cPP/rPO 50/50 200 C	11.06	5/16-18 Bolt	275	24.86	1.01	F Drill Bit	6.50 mm
457i	cPP/rPO 50/50 200 C	11.58	5/16-18 Bolt	335	28.93	1.18	F Drill Bit	6.50 mm
457i	cPP/rPO 50/50 200 C	11.58	5/16-18 Bolt	315	27.20	1.11	F Drill Bit	6.50 mm
456i	cPP/rPO 50/50 200 C	11.12	5/16-18 Bolt	295	26.53	1.08	F Drill Bit	6.50 mm

cPP/rPO 50/50 180 C								
440i	cPP/rPO 50/50 180 C	11.65	5/16-18 Bolt	465	39.91	1.62	F Drill Bit	6.50 mm
439ii	cPP/rPO 50/50 180 C	11.60	5/16-18 Bolt	440	37.93	1.54	F Drill Bit	6.50 mm
481i	cPP/rPO 50/50 180 C	11.03	5/16-18 Bolt	460	41.70	1.70	F Drill Bit	6.50 mm
439ii	cPP/rPO 50/50 180 C	11.60	5/16-18 Bolt	415	35.78	1.46	F Drill Bit	6.50 mm
454	cPP/rPO 50/50 180 C	12.02	5/16-18 Bolt	463	38.52	1.57	F Drill Bit	6.50 mm

cPPrPO 60/40 180 C								
496	cPP/rPO 60/40 180 C	9.62	5/16-18 Bolt	426	44.28	1.80	F Drill Bit	6.50 mm
500	cPP/rPO 60/40 180 C	9.29	5/16-18 Bolt	385	41.44	1.69	F Drill Bit	6.50 mm
514	cPP/rPO 60/40 180 C	9.53	5/16-18 Bolt	451	47.32	1.93	F Drill Bit	6.50 mm
514	cPP/rPO 60/40 180 C	9.53	5/16-18 Bolt	420	44.07	1.79	F Drill Bit	6.50 mm
496	cPP/rPO 60/40 180 C	9.62	5/16-18 Bolt	434	45.11	1.84	F Drill Bit	6.50 mm

cPP/rHDPE 50/50 180 C								
501i	cPP/rHDPE 50/50 180 C	11.57	5/16-18 Bolt	405	35.00	1.42	F Drill Bit	6.50 mm
501	cPP/rHDPE 50/50 180 C	11.57	5/16-18 Bolt	416	35.96	1.46	F Drill Bit	6.50 mm
501	cPP/rHDPE 50/50 180 C	11.57	5/16-18 Bolt	439	37.94	1.54	F Drill Bit	6.50 mm
501	cPP/rHDPE 50/50 180 C	11.57	5/16-18 Bolt	423	36.56	1.49	F Drill Bit	6.50 mm
510	cPP/rHDPE 50/50 180 C	11.20	5/16-18 Bolt	321	28.66	1.17	F Drill Bit	6.50 mm

cPP/rHDPE 70/30 180 C								
487i	cPP/rHDPE 70/30 180 C	8.17	5/16-18 Bolt	240	29.38	1.20	F Drill Bit	6.50 mm
497i	cPP/rHDPE 70/30 180 C	8.12	5/16-18 Bolt	245	30.17	1.23	F Drill Bit	6.50 mm
515	cPP/rHDPE 70/30 180 C	8.19	5/16-18 Bolt	299	36.51	1.49	F Drill Bit	6.50 mm
515	cPP/rHDPE 70/30 180 C	8.19	5/16-18 Bolt	346	42.25	1.72	F Drill Bit	6.50 mm
487i	cPP/rHDPE 70/30 180 C	8.17	5/16-18 Bolt	308	37.70	1.53	F Drill Bit	6.50 mm

rHDPE								
464	rHDPE	11.86	5/16-18 Bolt	360	30.35	1.24	F Drill Bit	6.50 mm
464	rHDPE	11.86	5/16-18 Bolt	379	31.96	1.30	F Drill Bit	6.50 mm
464	rHDPE	11.86	5/16-18 Bolt	365	30.78	1.25	F Drill Bit	6.50 mm
464	rHDPE	11.86	5/16-18 Bolt	310	26.14	1.06	F Drill Bit	6.50 mm
464	rHDPE	11.86	5/16-18 Bolt	329	27.74	1.13	F Drill Bit	6.50 mm
464	rHDPE	11.86	5/16-18 Bolt	360	30.35	1.24	F Drill Bit	6.50 mm
464	rHDPE	11.86	5/16-18 Bolt	355	29.93	1.22	F Drill Bit	6.50 mm

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)	Pilot Hole	Pilot Hole
cPET/rPET								
640	cPET/rPET	6.15	5/16-18 Bolt	300	48.78	1.99	F Drill Bit	6.50 mm
636	cPET/rPET	6.51	5/16-18 Bolt	350	53.76	2.19	F Drill Bit	6.50 mm
637	cPET/rPET	5.85	5/16-18 Bolt	325	55.56	2.26	F Drill Bit	6.50 mm
631	cPET/rPET	6.36	5/16-18 Bolt	370	58.18	2.37	F Drill Bit	6.50 mm
639	cPET/rPET	6.49	5/16-18 Bolt	358	55.16	2.25	F Drill Bit	6.50 mm
641	cPET/rPET	6.42	5/16-18 Bolt	327	50.93	2.07	F Drill Bit	6.50 mm
cPET								
644	cPET	4.32	5/16-18 Bolt	145	33.56	1.37	F Drill Bit	6.50 mm
649	cPET	4.29	5/16-18 Bolt	185	43.12	1.76	F Drill Bit	6.50 mm
652	cPET	4.32	5/16-18 Bolt	180	41.67	1.70	F Drill Bit	6.50 mm
647	cPET	4.45	5/16-18 Bolt	218	48.99	1.99	F Drill Bit	6.50 mm
653	cPET	4.21	5/16-18 Bolt	192	45.61	1.86	F Drill Bit	6.50 mm
644	cPET	4.48	5/16-18 Bolt	192	42.86	1.74	F Drill Bit	6.50 mm
rPET								
662	rPET	4.78	5/16-18 Bolt	310	64.85	2.64	F Drill Bit	6.50 mm
659	rPET	4.79	5/16-18 Bolt	313	65.34	2.66	F Drill Bit	6.50 mm
663	rPET	5.05	5/16-18 Bolt	375	74.26	3.02	F Drill Bit	6.50 mm
664	rPET	4.84	5/16-18 Bolt	367	75.83	3.09	F Drill Bit	6.50 mm
657	rPET	4.59	5/16-18 Bolt	319	69.50	2.83	F Drill Bit	6.50 mm
rPO								
543	rPO	11.97	5/16-18 Bolt	330	27.57	1.12	F Drill Bit	6.50 mm
543	rPO	11.97	5/16-18 Bolt	325	27.15	1.11	F Drill Bit	6.50 mm
543	rPO	11.97	5/16-18 Bolt	332	27.74	1.13	F Drill Bit	6.50 mm
543	rPO	11.97	5/16-18 Bolt	313	26.15	1.06	F Drill Bit	6.50 mm
543	rPO	11.97	5/16-18 Bolt	324	27.07	1.10	F Drill Bit	6.50 mm
cPP								
402	cPP	5.61	5/16-18 Bolt	231	41.18	1.68	F Drill Bit	6.50 mm
432	cPP	5.47	5/16-18 Bolt	258	47.17	1.92	F Drill Bit	6.50 mm
436	cPP	5.24	5/16-18 Bolt	280	53.44	2.18	F Drill Bit	6.50 mm
432	cPP	5.47	5/16-18 Bolt	262	47.90	1.95	F Drill Bit	6.50 mm
436	cPP	5.24	5/16-18 Bolt	237	45.23	1.84	F Drill Bit	6.50 mm

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)
rHDPE						
464	rHDPE	11.75	Common Nail	60	5.11	0.55
464	rHDPE	11.75	Common Nail	59	5.02	0.54
464	rHDPE	11.75	Common Nail	51	4.34	0.47
464	rHDPE	11.75	Common Nail	65	5.53	0.60
464	rHDPE	11.75	Common Nail	60	5.11	0.55
cPP/rPO 60/40 180 C						
500	cPP/rPO 60/40 180 C	9.82	Common Nail	52	5.30	0.57
500	cPP/rPO 60/40 180 C	9.82	Common Nail	52	5.30	0.57
500	cPP/rPO 60/40 180 C	9.82	Common Nail	49	4.99	0.54
514	cPP/rPO 60/40 180 C	9.64	Common Nail	53	5.50	0.59
496	cPP/rPO 60/40 180 C	9.62	Common Nail	49	5.09	0.55
500	cPP/rPO 60/40 180 C	9.82	Common Nail	40	4.07	0.44
cPP/rHDPE 50/50 180 C						
501	cPP/rHDPE 50/50 180 C	11.46	Common Nail	56	4.89	0.53
501	cPP/rHDPE 50/50 180 C	11.46	Common Nail	53	4.62	0.50
510	cPP/rHDPE 50/50 180 C	11.27	Common Nail	46	4.08	0.44
510	cPP/rHDPE 50/50 180 C	11.27	Common Nail	49	4.35	0.47
510	cPP/rHDPE 50/50 180 C	11.27	Common Nail	50	4.44	0.48

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)
cPP/rPO 50/50 200 C						
456	cPP/rPO 50/50 200 C	10.91	Common Nail	62	5.68	0.61
456	cPP/rPO 50/50 200 C	10.91	Common Nail	46	4.22	0.45
457	cPP/rPO 50/50 200 C	11.38	Common Nail	53	4.66	0.50
462	cPP/rPO 50/50 200 C	11.66	Common Nail	63	5.40	0.58
450	cPP/rPO 50/50 200 C	10.83	Common Nail	59	5.45	0.59
cPP/rPO 50/50 180 C						
440	cPP/rPO 50/50 180 C	11.86	Common Nail	62	5.23	0.56
440	cPP/rPO 50/50 180 C	11.86	Common Nail	59	4.97	0.54
439	cPP/rPO 50/50 180 C	11.63	Common Nail	60	5.16	0.56
482	cPP/rPO 50/50 180 C	11.52	Common Nail	43	3.73	0.40
481	cPP/rPO 50/50 180 C	11.00	Common Nail	40	3.64	0.39
440	cPP/rPO 50/50 180 C	11.86	Common Nail	55	4.64	0.50
cPP/rHDPE 70/30 180 C						
497	cPP/rHDPE 70/30 180 C	8.16	Common Nail	42	5.15	0.56
515	cPP/rHDPE 70/30 180 C	8.29	Common Nail	48	5.79	0.62
497	cPP/rHDPE 70/30 180 C	8.16	Common Nail	43	5.27	0.57
487	cPP/rHDPE 70/30 180 C	8.03	Common Nail	41	5.11	0.55
515	cPP/rHDPE 70/30 180 C	8.29	Common Nail	41	4.95	0.53
rPO						
543	rPO	11.97	Common Nail	32	2.67	0.29
543	rPO	11.97	Common Nail	29	2.42	0.26
543	rPO	11.97	Common Nail	41	3.43	0.37
543	rPO	11.97	Common Nail	40	3.34	0.36
543	rPO	11.97	Common Nail	42	3.51	0.38
cPP						
402	cPP	5.61	Common Nail	42	7.49	0.81
432	cPP	5.47	Common Nail	34	6.22	0.67
436	cPP	5.24	Common Nail	35	6.68	0.72
402	cPP	5.61	Common Nail	38	6.77	0.73
432	cPP	5.47	Common Nail	45	8.23	0.89
Pine Wood						
1	Pine Wood	17.5	Common Nail	13	0.74	0.08
1	Pine Wood	17.5	Common Nail	13	0.74	0.08
1	Pine Wood	17.5	Common Nail	12	0.69	0.07
1	Pine Wood	17.5	Common Nail	12	0.69	0.07
1	Pine Wood	17.5	Common Nail	13	0.69	0.08
HDPE						
464	rHDPE	11.75	Ring Shank Nail	117	9.96	1.01
464	rHDPE	11.75	Ring Shank Nail	87	7.40	0.75
464	rHDPE	11.75	Ring Shank Nail	101	8.60	0.87
464	rHDPE	11.75	Ring Shank Nail	99	8.43	0.85
464	rHDPE	11.75	Ring Shank Nail	98	8.34	0.84
cPP/rPO 60/40 180 C						
500	cPP/rPO 60/40 180 C	9.82	Ring Shank Nail	114	11.61	1.17
500	cPP/rPO 60/40 180 C	9.82	Ring Shank Nail	74	7.54	0.76
514	cPP/rPO 60/40 180 C	9.64	Ring Shank Nail	89	9.23	0.93
496	cPP/rPO 60/40 180 C	9.62	Ring Shank Nail	105	10.91	1.10
514	cPP/rPO 60/40 180 C	9.64	Ring Shank Nail	78	8.09	0.82
500	cPP/rPO 60/40 180 C	9.82	Ring Shank Nail	103	10.49	1.06

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)
cPP/rHDPE 50/50 180 C						
501	cPP/rHDPE 50/50 180 C	11.46	Ring Shank Nail	100	8.73	0.88
501	cPP/rHDPE 50/50 180 C	11.46	Ring Shank Nail	96	8.38	0.85
510	cPP/rHDPE 50/50 180 C	11.27	Ring Shank Nail	110	9.76	0.99
510	cPP/rHDPE 50/50 180 C	11.27	Ring Shank Nail	84	7.45	0.75
501	cPP/rHDPE 50/50 180 C	11.46	Ring Shank Nail	115	10.03	1.01
510	cPP/rHDPE 50/50 180 C	11.27	Ring Shank Nail	104	9.23	0.93
cPP/rPO 50/50 200 C						
456	cPP/rPO 50/50 200 C	10.91	Ring Shank Nail	74	6.78	0.69
457	cPP/rPO 50/50 200 C	11.38	Ring Shank Nail	54	4.75	0.48
450	cPP/rPO 50/50 200 C	10.83	Ring Shank Nail	81	7.48	0.76
483	cPP/rPO 50/50 200 C	11.42	Ring Shank Nail	65	5.69	0.58
462	cPP/rPO 50/50 200 C	11.50	Ring Shank Nail	52	4.52	0.46
483	cPP/rPO 50/50 200 C	11.24	Ring Shank Nail	73	6.49	0.66
457	cPP/rPO 50/50 200 C	11.32	Ring Shank Nail	77	6.80	0.69
cPP/rPO 50/50 180 C						
440	cPP/rPO 50/50 180 C	11.86	Ring Shank Nail	114	9.61	0.97
481	cPP/rPO 50/50 180 C	11.00	Ring Shank Nail	87	7.91	0.80
454	cPP/rPO 50/50 180 C	11.64	Ring Shank Nail	86	7.39	0.75
459	cPP/rPO 50/50 180 C	11.73	Ring Shank Nail	99	8.44	0.85
439	cPP/rPO 50/50 180 C	11.63	Ring Shank Nail	105	9.03	0.91
cPP/rHDPE 70/30 180 C						
497	cPP/rHDPE 70/30 180 C	8.16	Ring Shank Nail	68	8.33	0.84
515	cPP/rHDPE 70/30 180 C	8.16	Ring Shank Nail	87	10.66	1.08
487	cPP/rHDPE 70/30 180 C	8.03	Ring Shank Nail	70	8.72	0.88
497	cPP/rHDPE 70/30 180 C	8.16	Ring Shank Nail	73	8.95	0.90
515	cPP/rHDPE 70/30 180 C	8.16	Ring Shank Nail	89	10.91	1.10
PO						
543	rPO	11.97	Ring Shank Nail	52	4.34	0.44
543	rPO	11.97	Ring Shank Nail	63	5.26	0.53
543	rPO	11.97	Ring Shank Nail	74	6.18	0.62
543	rPO	11.97	Ring Shank Nail	73	6.10	0.62
543	rPO	11.97	Ring Shank Nail	55	4.59	0.46
cPP						
436	cPP	5.24	Ring Shank Nail	60	11.45	1.16
432	cPP	5.47	Ring Shank Nail	60	10.97	1.11
402	cPP	5.61	Ring Shank Nail	62	11.05	1.12
436	cPP	5.24	Ring Shank Nail	79	15.08	1.52
432	cPP	5.47	Ring Shank Nail	80	14.63	1.48
402	cPP	5.61	Ring Shank Nail	76	13.55	1.37
Pine Wood						
1	Pine Wood	17.5	Ring Shank Nail	35	2.00	0.22
1	Pine Wood	17.5	Ring Shank Nail	40	2.29	0.25
1	Pine Wood	17.5	Ring Shank Nail	37	2.11	0.23
1	Pine Wood	17.5	Ring Shank Nail	36	2.06	0.22
1	Pine Wood	18.5	Ring Shank Nail	37	3.06	0.22

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)
rHDPE						
464	rHDPE	11.75	Spiral Shank Nail	78	6.64	0.60
464	rHDPE	11.75	Spiral Shank Nail	80	6.81	0.62
464	rHDPE	11.75	Spiral Shank Nail	84	7.15	0.65
464	rHDPE	11.75	Spiral Shank Nail	82	6.98	0.63
464	rHDPE	11.75	Spiral Shank Nail	78	6.64	0.60
cPP/rPO 60/40 180 C						
500	cPP/rPO 60/40 180 C	9.82	Spiral Shank Nail	70	7.13	0.65
500	cPP/rPO 60/40 180 C	9.82	Spiral Shank Nail	62	6.31	0.57
514	cPP/rPO 60/40 180 C	9.64	Spiral Shank Nail	58	6.02	0.55
514	cPP/rPO 60/40 180 C	9.64	Spiral Shank Nail	60	6.22	0.57
514	cPP/rPO 60/40 180 C	9.64	Spiral Shank Nail	63	6.54	0.59
cPP/rHDPE 50/50 180 C						
501	cPP/rHDPE 50/50 180 C	11.46	Spiral Shank Nail	81	7.07	0.64
501	cPP/rHDPE 50/50 180 C	11.46	Spiral Shank Nail	64	5.58	0.51
510	cPP/rHDPE 50/50 180 C	11.27	Spiral Shank Nail	79	7.01	0.64
510	cPP/rHDPE 50/50 180 C	11.27	Spiral Shank Nail	78	6.92	0.63
510	cPP/rHDPE 50/50 180 C	11.27	Spiral Shank Nail	78	6.92	0.63
cPP/rPO 50/50 200 C						
462	cPP/rPO 50/50 200 C	11.69	Spiral Shank Nail	59	5.05	0.46
456	cPP/rPO 50/50 200 C	10.91	Spiral Shank Nail	64	5.87	0.53
457	cPP/rPO 50/50 200 C	11.54	Spiral Shank Nail	63	5.46	0.50
483	cPP/rPO 50/50 200 C	11.34	Spiral Shank Nail	60	5.29	0.48
462	cPP/rPO 50/50 200 C	11.69	Spiral Shank Nail	74	6.33	0.58
cPP/rPO 50/50 180 C						
481	cPP/rPO 50/50 180 C	11	Spiral Shank Nail	73	6.64	0.60
440	cPP/rPO 50/50 180 C	11.86	Spiral Shank Nail	69	5.82	0.53
482	cPP/rPO 50/50 180 C	11.52	Spiral Shank Nail	70	6.08	0.55
481	cPP/rPO 50/50 180 C	10.93	Spiral Shank Nail	79	7.23	0.66
454	cPP/rPO 50/50 180 C	11.64	Spiral Shank Nail	73	6.27	0.57
cPP/rHDPE 70/30 180 C						
515	cPP/rHDPE 70/30 180 C	8.29	Spiral Shank Nail	61	7.36	0.67
515	cPP/rHDPE 70/30 180 C	8.16	Spiral Shank Nail	64	7.84	0.71
497	cPP/rHDPE 70/30 180 C	7.96	Spiral Shank Nail	60	7.54	0.69
487	cPP/rHDPE 70/30 180 C	8.03	Spiral Shank Nail	55	6.85	0.62
497	cPP/rHDPE 70/30 180 C	7.96	Spiral Shank Nail	58	7.29	0.66
rPO						
543	rPO	11.97	Spiral Shank Nail	40	3.34	0.30
543	rPO	11.97	Spiral Shank Nail	50	4.18	0.38
543	rPO	11.97	Spiral Shank Nail	50	4.18	0.38
543	rPO	11.97	Spiral Shank Nail	48	4.01	0.36
543	rPO	11.97	Spiral Shank Nail	55	4.59	0.42
cPP						
402	cPP	5.61	Spiral Shank Nail	57	10.16	0.92
432	cPP	5.47	Spiral Shank Nail	54	9.87	0.90
436	cPP	5.24	Spiral Shank Nail	50	9.54	0.87
432	cPP	5.47	Spiral Shank Nail	56	10.24	0.93
436	cPP	5.24	Spiral Shank Nail	48	9.16	0.83

Sample	Compoisition	Thickness (mm)	Fastener	Pull-Out Force (kg)	Pull-Out Force/Thickness (kg/mm)	Pull-Out Force/Contact Area (kg/mm^2)
Pine Wood						
1	Pine Wood	17.5	Spiral Shank Nail	55	3.14	0.29
1	Pine Wood	17.5	Spiral Shank Nail	50	2.86	0.26
1	Pine Wood	17.5	Spiral Shank Nail	49	2.80	0.25
1	Pine Wood	17.5	Spiral Shank Nail	50	2.86	0.26
1	Pine Wood	18.5	Spiral Shank Nail	51	2.86	0.25

Several things were observed during the set-up of the fastener pull-out tests but not tested quantitively. Fasteners were able to be driven in relatively close to existing holes in the material from precious fastener pull-out tests without effecting the holding capabilities of the material on the fastener. It was found that fasteners could be spaced 15 mm to 25 mm away from the edge of an existing hole and still retain full holding strength.

It was observed that driving a screw into the composite materials by hand with a screwdriver was very difficult and required much more force than driving a screw into wood. Even though the composite samples were much thinner than the pieces of wood used, to drive a wood screw into one of the composite materials required a great deal of strength. We wanted to reduce the amount of torque required to drive a screw into the composite material so that it would be comparable to the torque required to drive a screw into wood by increasing the size of the pilot hole used for the composites.

The max amount of torque used when hand turning either the #8 or #12 wood screw into a piece of common pine with the recommended pilot hole size using a Philips screwdriver was measured and then divided by the thickness of the sample to form a baseline measurement. The same pilot hole size was drilled into samples of the composites and polymers. The max torque was measured and divided by the thickness and found to be much larger than the baseline measurement, up to 4 times the max torque of the wood. It was found that by using a drill bit 0.79 mm (1/32″ or 0.03″) bigger than the recommended pilot hole size for a given wood screw would bring the max torque/sample thickness for the composite materials much closer to that of wood. The fastener pull-out force of the composite materials with wood screws was then tested with both sizes of pilot holes and it was found that the pull-out force was not significantly affected for the bigger pilot hole size. It was decided to conduct testing with the bigger pilot hole sizes with the composites and pure polymer samples with wood screws so that the tests were being done with a pilot hole size that would make it able to turn a screw by hand.

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