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Experimental investigation of mechanical behaviour and load-bearing capacity of fibreglass and metal-reinforced polypropylene sanitary manhole covers

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ABSTRACT

Sanitary manhole covers, such as infrastructure lines, drainage, and stormwater, are important in drainage systems. In recent years, there have been intensive attempts to improve the performance of these covers and reduce their costs. This study investigated the mechanical behaviour and load-bearing capacity of polypropylene manhole covers modified using two methods. In the first modification, covers were strengthened by injecting ribs composed of 15 wt.% and 30 wt.% glass fibres. In the second modification, a steel spiral rod was installed along the circumference of the cover. Compression tests were conducted using a universal testing machine equipped with ZwickRoell Xforce load cells to evaluate the effectiveness of these modifications. Contrary to expectations, the results showed a 12.36 kN average decrease in the cover load capacity when there was a 15 wt.% content of glass fibres, indicating a 13.46% weakening compared to the traditional version of pure polypropylene. In contrast, the variant with a 30 wt.% filler content exhibits a 19.31 kN decrease in load-bearing capacity, resulting in a 21.03% weakening compared to the pure polypropylene cover. When the spiral steel rod was added, the result was a significant reduction in the cross-sectional area of the circumferential rib, leading to cracking with an average force value of 86.21 kN. This was lower than the load capacity of the variant without a bar, which was 91.82 kN.

Keywords: mechanical behaviour, load-bearing capacity, manhole cover, strengthening ribs, polypropylene, glass fibres, cracks.

INTRODUCTION

For the sewerage, drainage, stormwater, and infrastructure lines in modern cities to function regularly and without problems, it is necessary to use sanitary manhole covers in certain places at certain distances on the lines. The material of the selected manhole covers can vary based on various factors, including the shape of the manhole and the function of the intended manhole [1]. Traditionally, manhole covers were constructed using precast concrete [2]. They were also made of cast iron and wrought iron, where the covers are heavy, durable, and weigh up to 100 kg [3]. Due to technological advances in recent years, the use of polymers and composite materials such as polyethylene, polypropylene and fiberglass has increased in popularity as sanitary manhole covers. Polyethylene and polypropylene sanitary manhole covers are corrosion-resistant [4], easier to handle, reduce manual labour, and weigh a third less than cast iron ones [5]. In addition to being safer, they are much cheaper and are rarely stolen [6]. The most critical considerations when choosing sanitary manhole covers are load-bearing capacity, corrosion resistance, and ease of access.

Load-bearing capacity studies are of great importance in engineering industries [7]. Adding ribs is essential at all levels, whether the materials are pure or composite [8–9]. Studies on sanitary manholes have varied in design, materials, and load-bearing capacity. Another category discussed the possibility of reinforcing the sanitary manhole and creating composite materials with additional load-bearing capacity or weight reduction. However, the studies that concentrate on sanitary manhole covers are scarce, and those that explore the potential for reinforcing these covers are virtually non-existent. Abbas et al. [10] investigated a new design of two separate manholes to withstand high loads and prevent fouling in separate sewage systems. Their studies examined two models: an experimental one and a mathematical one, both based on the 3D Quarter Symmetric FEA Model. Experiments confirm that displays up to 3.5 mm can affect the soil surrounding the manhole under medium and heavy loads (50 to 90 KN). Abbas et al. [11] introduced an experimental investigation for the live load in buried manholes combined with a modified design based on a large external surface area. They employed a novel method to replicate the live load on a manhole, which involved integrating a hydraulic rig with a sand-filled cylindrical composition. Their results contributed to a deeper understanding of the impact of the external surface of the manhole on the endurance under various loads, as the developed model was more endemic than the traditional model of the manhole, especially at heavy loads. Entezarmahdi et al. [12] conducted three-edge load tests to investigate the feasibility of experimentally rehabilitating manholes without trenching by relining them with epoxy, polyurethane, and multi-structural liners as well as using the finite element method. They conducted many tests by adopting several ASTM standards, such as C-39, C-293, C-76, and C-497, according to the three-edge-bearing test for large pipe diameters that reach 24 in. Their findings showed a significant improvement in the overall performance of the concrete samples under compression and flexure. In the same context, Kaushal et al. [13] used cement mortar, epoxy, and polyurethane as lining materials for the rehabilitation of manholes. The experimental results supported by finite element analysis showed that the method contributed to a very encouraging improvement in structural performance. Epoxy-manufactured linings can significantly boost endurance forces to 133%, whereas cementitious-manufactured linings can also significantly increase endurance forces to 127%. However, they are significantly larger than polyurethane-manufactured linings, which only reach 52%. Furthermore, once the lining reaches a thickness of 7 mm, it no longer affects the flexural strength. Sakhakarmi et al. [14] favoured polymer concrete manholes over cement concrete manholes in a study based on life-cycle installation costs. The study reveals that cement concrete manholes require frequent maintenance and replacement due to their high vulnerability in corrosive environments. Despite these findings, they acknowledged that their dependence on cost calculations for only 50 years undermines the data's reliability. The study by Goff et al. [15] noted a significant increase in the use of reinforcement in the sewerage sector through its inclusion in large infrastructure projects in Canada. This study is regarded as highly reliable due to its reliance on projects costing $650 for sewage openings with a diameter of 1.6 to 2.5 m and a depth of up to 65 m. Its goal was to study the possibility of using Glass-Fibre Reinforced Plastic (GRP) instead of High-Density Polyethylene (HDPE) for cost considerations. It demonstrated that using glass-fibre reinforced plastic would change the design philosophies assumed with better cost and time savings while maintaining safety and quality considerations. Royer [16, 17] reviewed the possibility of using sprayed geopolymer mortar in the rehabilitation of sewerage systems to overcome the traditional problems of repair and replacement, which are the large size of excavations required for each repair or replacement operation and concluded that this proposed method could give good results, especially since a third party documented it. Jie Sun et al. [18] used a simplified and effective method to address the leakage problems caused by temperature changes in the manhole connections of glass fibre-reinforced plastic, where the proposed method utilised resin wrapping at the spout. The issue was resolved by covering and reducing the temperature deformation of light on glass fibre-reinforced plastic mortar pipes using blankets. Engineering practice has demonstrated the method's simplicity, practicality, dependability, and positive effects on the economy, society, and environment. Despite the scarcity of studies on reinforcement in manhole covers, Calin Itu et al. [19] deserved praise for their experimental and simulation model of a sandwich composite manhole. Their model consisted of layers of orientated strand board reinforced with glass fibres. The manhole cover was manufactured using a sandwich composite of two layers of oriented strand board surrounded by glass fibres. The proposed model has contributed to enhancing the stiffness-weight ratio. The external load-bearing capacity of the developed manhole cover reached 2 kN, while the maximum stress obtained was 49 MPa. Moreover, Bhopatrao and Kewate [20] fabricated eco-friendly manhole covers using bamboo reinforcement and concluded that the overall cost could be reduced by 36% while maintaining the required strength. The cost of reinforcement and treatment of steel manhole covers is 300% greater than that of bamboo manhole covers, so the developed bamboo model can also contribute to reducing manhole cover theft.

Studies on manhole covers have varied in design, materials used, and load-bearing capacity. Another category discussed the possibility of strengthening manhole covers and creating composite materials with additional load bearing capacity or weight reduction. However, the studies focusing on manhole covers are rare, and those exploring the possibility of strengthening these covers are almost non-existent. In conclusion, the possibility of reinforcing manhole covers has not been sufficiently studied, and a deep understanding of the load-bearing capacity of strengthened manhole covers requires further research. In this study, two experimental models were prepared to enhance manhole covers made of polypropylene. The first was based on strengthening via additional radial ribs, while the second was based on adding different percentages of fibreglass. Load-bearing tests were conducted on the developed models, and comparisons were made between all cases. The work aimed to indicate the reasons for reduced load-bearing capacity during subsequent attempts to strengthen the cover.

MATERIALS AND METHODS

The study focused on the load-bearing capacity tests on three different models of sanitary manhole covers. The first model was made entirely of polypropylene; the second was reinforced with radial ribs made of polypropylene with a certain percentage of glass fibres, and the third was made of polypropylene strengthened with a spiral steel rod which considered as circumferential ribs. The basic model was manufactured entirely from polypropylene. Figure 1 indicates the basic dimensions and the approved design. It should be noted that the other details are not authorized to be published in this research, which is an element of the research and development work that constitutes the product implementation stage in serial production.

In an attempt to increase the load-bearing capacity of the cover, the manhole cover geometry was modified by adding radial ribs, which are marked in blue in Figure. 2. The modified cover was manufactured from polypropylene (base material) with a filler in the form of chopped glass fibres. Two different fibre contents were used, i.e., 15 wt.% and 30 wt.%. The new mixture of polypropylene and glass fibres produced the additional radial ribs. The plastic manufacturer's data justifies using such materials with fillers, stating that polypropylene with filler in the discussed form has a higher strength than pure polypropylene, which can be up to 130%.

The last modification of the cover is done using a spiral steel rod, which is considered as additional circumferential ribs, as shown in blue in Figure 3. The modification involved injecting a steel rod spiral with a diameter of 8 mm into the lower part of the peripheral rib. A spiral with a pitch of 16 mm and 1.4 turns was used. The justification for using such structural reinforcement was the observations made at the stage of preliminary tests, which showed cracking around the circumference of the rib at a load significantly lower than the required load capacity. According to operational requirements, the cover in question must carry a load of 120 kN applied by a steel punch

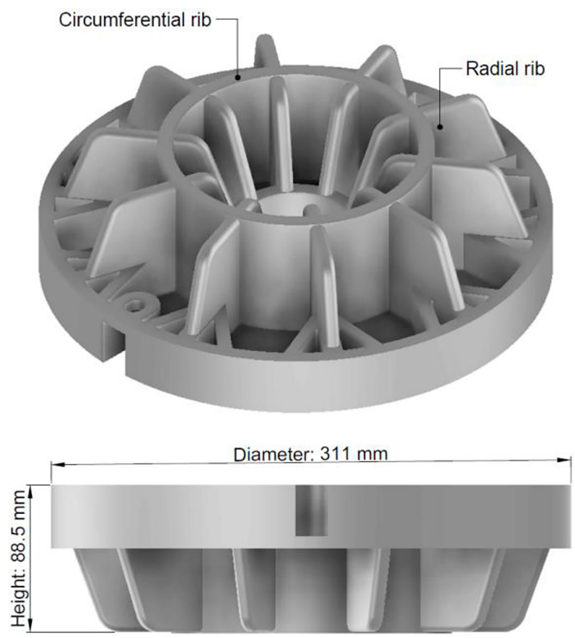

Figure 1. Main primary design and dimensions of the sewage chamber cover (Sample I)

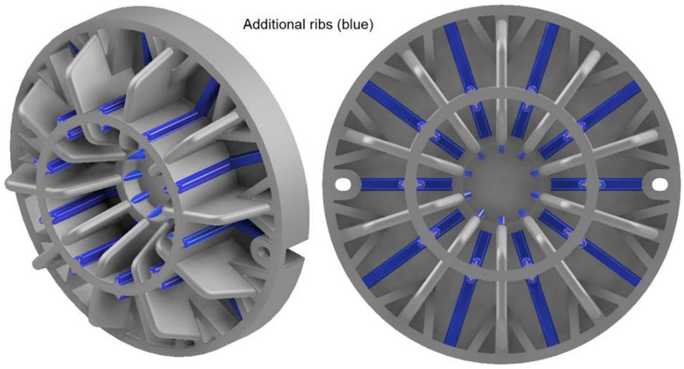

Figure 2. Additional radial ribs (blue) from polypropylene and glass fibres (Sample II)

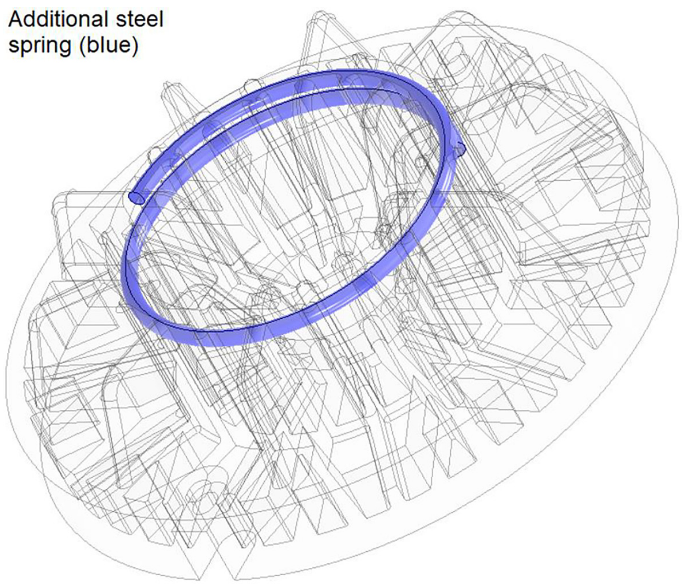

Figure 3. Additional circumferential ribs of spiral steel rod ((blue) (Sample III)

with dimensions shown in Figure 4. ZwickRoell Xforce load cells (ZwickRoell, Borken, Germany) were used to measure the load capacity of the specimens. These load cells are ideal for tensile, compression and bending tests and are unaffected by parasitic changes, such as temperature variations, torque, or trans-verse forces.

RESULTS AND DISCUSSION

Effect of glass fibre reinforcement

Several samples were manufactured, ranging from manhole covers made of pure polypropylene to those reinforced with additional glass fibre ribs. In order to determine these additional effects, load capacity tests were carried out using ZwickRoell Xforce load cells (ZwickRoell, Borken, Germany). A comparison was made between the variant with the primary cover model (pure polypropylene) and the cover reinforced with as additional radial glass fibre ribs. The average loading capacity of the manhole covers was determined by conducting compression tests on three specimens for each case. The results were averaged to provide a representative value for the loading capacity. Moreover, the standard deviation (SD) was calculated to quantify the variability among the specimens and ensure the reliability of the measurements. Using the SD approach ensured character analysis of the load-bearing capacity for the tested covers. The average load-bearing capacity for the primary cover model was 96.62 kN (SD=0.57 kN). In contrast, contrary to expectations, the load-bearing capacity decreased to an average value of 91.82 kN (SD=0.82 kN) in the case of additional reinforcement with glass fibre ribs. Figure 5 shows representative

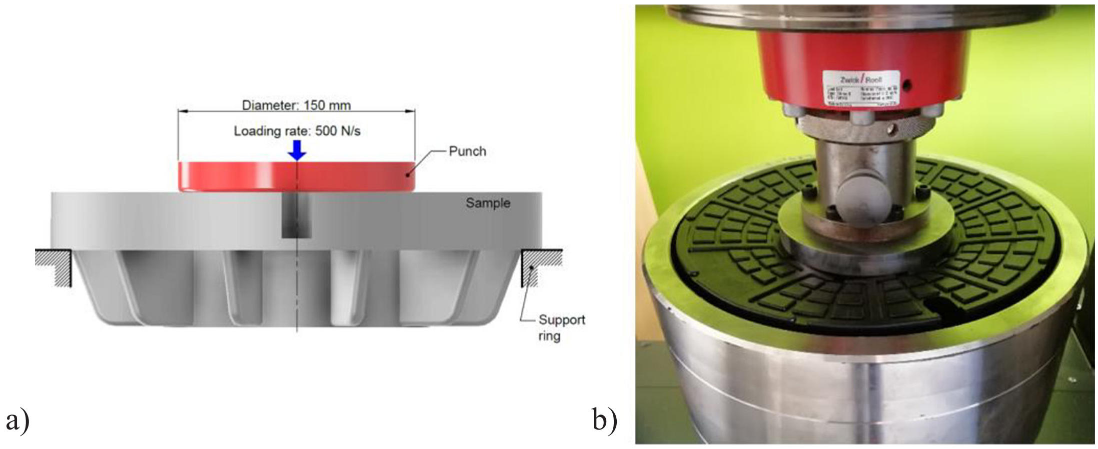

Figure 4. Capacity loading test (a) loading values on manhole cover and (b) actual view

force-displacement curves for the considered variants; based on them, it can be concluded that additional ribs significantly increase the stiffness of the cover. This steeper slope indicates increased stiffness, reflecting a more excellent resistance to deformation under the applied load. Although the ultimate load-bearing capacity slightly decreased, the improved stiffness of the rib-reinforced covers enhances their ability to maintain shape under operational loads, as supported by similar findings in the literature [21–22]. The hypothetical cause of the reduction in load capacity is the stress concentration phenomenon, which could have occurred in the connection of additional radial ribs with the circumferential rib [23–24].

For a more detailed analysis, a basic visual test was examined for the manhole cover with and without glass fibre reinforcement (Figure 6). The visual test of the covers involved a thorough inspection to identify any surface defects, cracks, or deformations that occurred during or after the load-bearing tests. The inspection focused on areas of high stress, particularly near the reinforced ribs and steel spiral rod, where damage was most likely to initiate. This evaluation assessed the structural integrity and quality of the covers, ensuring that any potential failure modes or weaknesses were documented. Figures 6a and b show the front and back of the cover without any glass fibre reinforcement. The cover appears more positively under loading because the front is free of visible defects (Figure 6a) and has a few internal rib cracks on the back (Figure 6b). The analysis of the cover variant with additional reinforcing ribs revealed cracks spreading radially in three directions from the centre of the cover on its upper surface (Figure 6c). The view of the underside confirmed that the central part of the cover suffered radial cracks throughout the thickness of the material (Figure 6d). Notably, these cracks

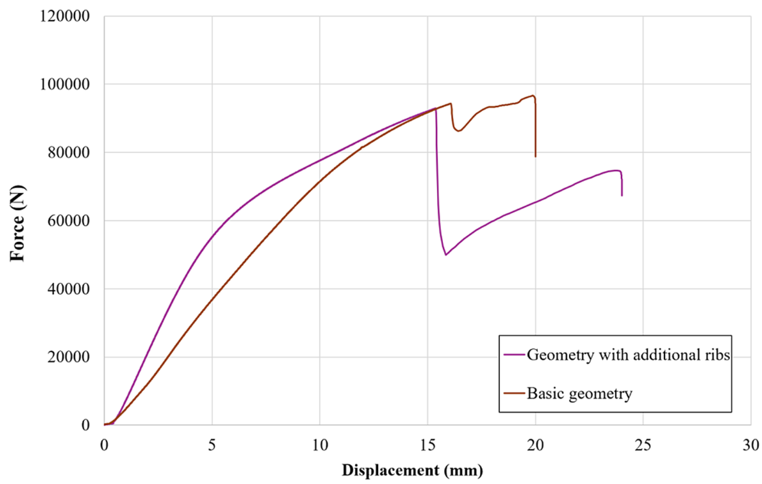

Figure 5. Effect of additional ribs on manhole cover compared with traditional cover according to force-displacement curves

occurred with a smaller displacement of the load-causing punch than in destroying the cover with basic geometry. Consequently, the circumferential rib of this version transferred the load through deformation, thereby preventing the main surface of the cover from cracking. However, introducing additional ribs stiffened the circumferential rib, significantly reducing the possibility of its deformation due to stretching along the circumference. This, in turn, prevented the cover surface from cracking due to excessive stiffness. The circumferential rib in the variant with additional stiffening was caused by the accumulation of stresses caused by the additional ribs. Such cracks occurred in eleven locations. In several cases, a crack was observed directly next to the additional ribs on both sides.

Effect of glass fibre percentage ratio on loading capacity

In the test shown in Figure 7, typical curves were found for covers made of pure PP and covers made of PP with a filler of glass fibres that had two different amounts (15 wt.% and 30 wt.%). It was assumed that glass fibre reinforcement would lead to higher load-bearing manhole covers. Tests, however, showed that covers made of filled plastic have a lower load-bearing capacity than the traditional version made of pure PP, which had an average load-bearing capacity of 91.82 kN. Thus, increasing the content of chopped glass fibres reduces the load-bearing capacity of the cover. Figure 7 shows the average force-displacement curves for three specimens tested in each case for pure PP, PP + 15% fibre glass, and PP + 30% fibre glass, respectively. The average value of the cover load capacity decreased by 12.36 kN when there was a 15 wt.% content of glass fibres, representing a 13.46% weakening compared to the traditional version of pure PP. In contrast, the variant with a 30 wt.% filler content shows a 19.31 kN decrease in load-bearing capacity, resulting in a 21.03% weakening compared to the pure PP cover.

The analysis of the test results indicates that in the case of the last variant considered, the dispersion of the load capacity is significant, as it amounts to 2.68 kN. For the cover made of unfilled plastic (SD: 0.82 kN) and with 15 wt.% fibre content (SD: 0.71 kN), the results were satisfactorily repeatable. This phenomenon may indicate an

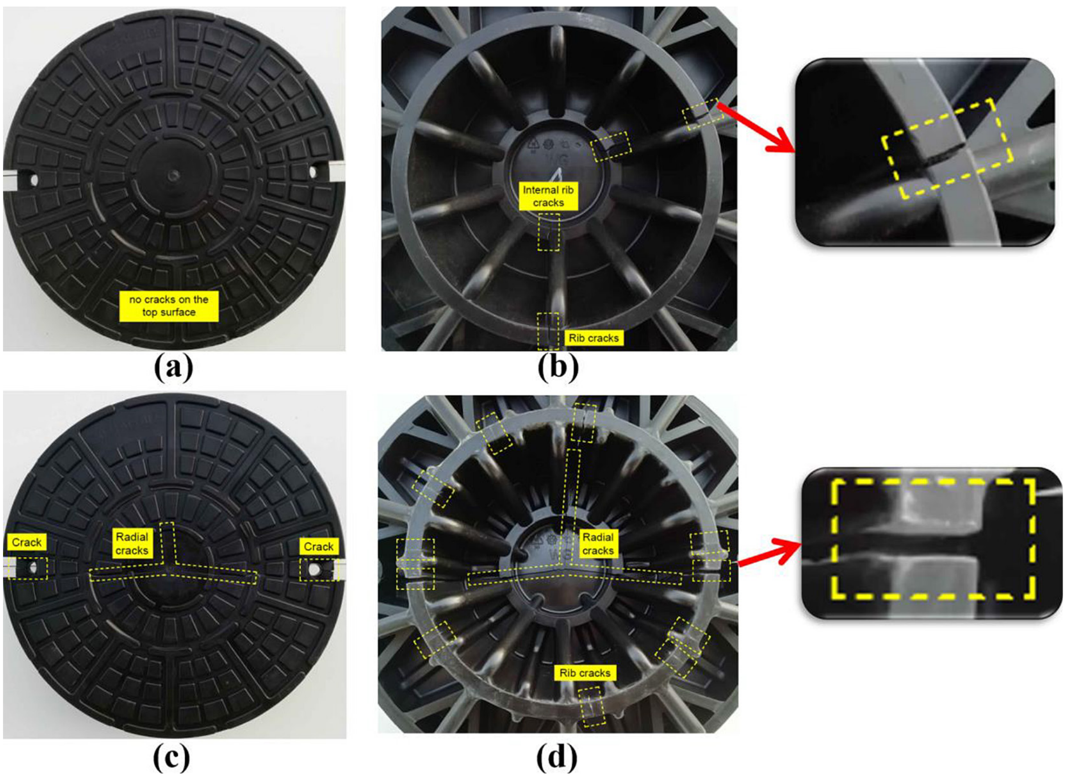

Figure 6. Influence of glass fibre reinforcement on the load-bearing capacity of the cover (a) front side without reinforcement, (b) back side without reinforcement, (c) front side with reinforcement, and (d) back side with reinforcement

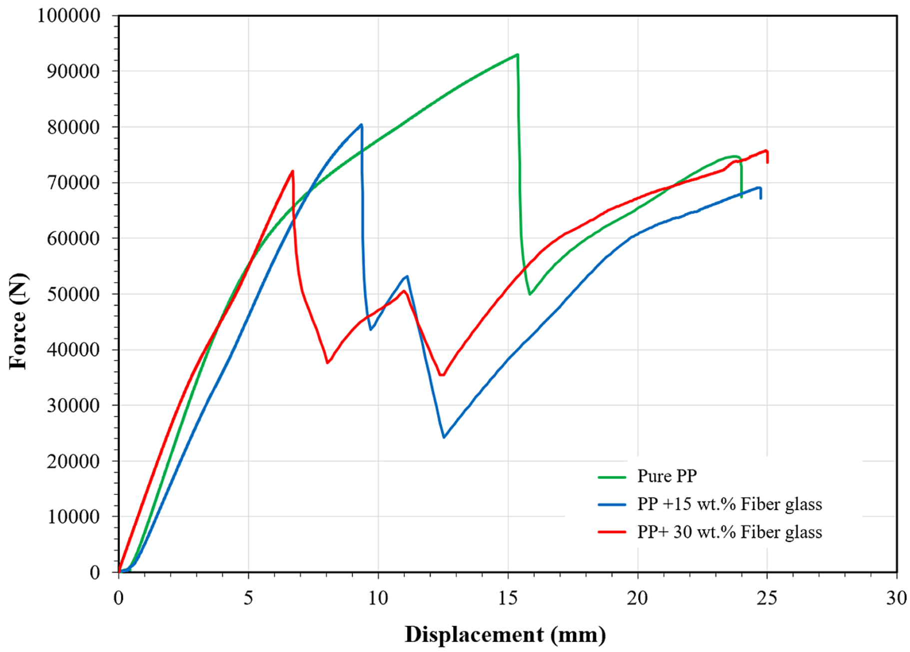

Figure 7. The force-displacement curves for pure PP, PP + 15 wt% fibre glass, and PP + 30 wt% fibre glass show the effect of the fibre glass percentage on the manhole cover compared to a pure propylene cove

uneven distribution of fibres in the structure of a material with complex geometry.

Effect of glass fibres percentage ratio on microstructure

In this study, the JEOL JSM-6610A was used as a scanning electron microscope (SEM). The SEM has a backscattered electron (BSE) detector with a 20 kV accelerating voltage and 40 nA current. In order to determine the reasons why the addition of fibres leads to a reduction in the load-bearing capacity of the cover, the crack surfaces of the peripheral rib were analysed for variants with different contents of the considered filler. Figures 8a and b show different fracture surface areas of the cover with 15 wt.% fibreglass content. Observations of the selected area reveal a non-uniform distribution of fibres in the mate-material volume, with significant fibre clusters visible (Figure 8a) and areas with negligible fibre density (Figure 8a). Therefore, uneven fibre dispersion resulting from plastic injection into a mould with multidirectional geometry may be one of the reasons for the weakening of the cover structure [25]. However, the direction of fibre arrangement, which in most cases is parallel or oblique to the crack surface, has a more significant impact on the reduction of the load-bearing capacity [26–27]. To further highlight the fibres, their structure, and potential breakage, images were examined at higher magnifications (850x and 1300x), as shown in Figure 8c and d. In fact, no broken fibres that would be stretched during loading were observed at the fractures. The dominant direction of the fibres coincides with the direction of the material flow during the injection process, and a rib with cylindrical geometry is created as a result of the material flow in the axial direction, which determines the dominant direction of the fibres. The reinforcing fibres then provide the desired strengthening effect when subjected to stretching. At the same time, their transverse or diagonal orientation towards the direction of the load mainly causes the polypropylene material to be torn off from the surface of the fibres, and the fibres are torn off and not stretched. The adhesion between glass fibres and polypropylene has significantly lower strength than the polypropylene material, hence the weakening of the structure of the reinforced material.

Similar phenomena, i.e., uneven fibre dispersion and the dominant, parallel direction of fibre alignment, were observed for the variant with 30 wt.% glass fibre content (Figures 9 a and b). The demonstrated decrease in the load-bearing capacity of the cover with an increase in the reinforcement content can be explained by the principle of proportionality. If there are statistically twice as many relatively weak fibre-polypropylene adhesive connections in the material structure, then the load-bearing capacity is proportionally lower [28].

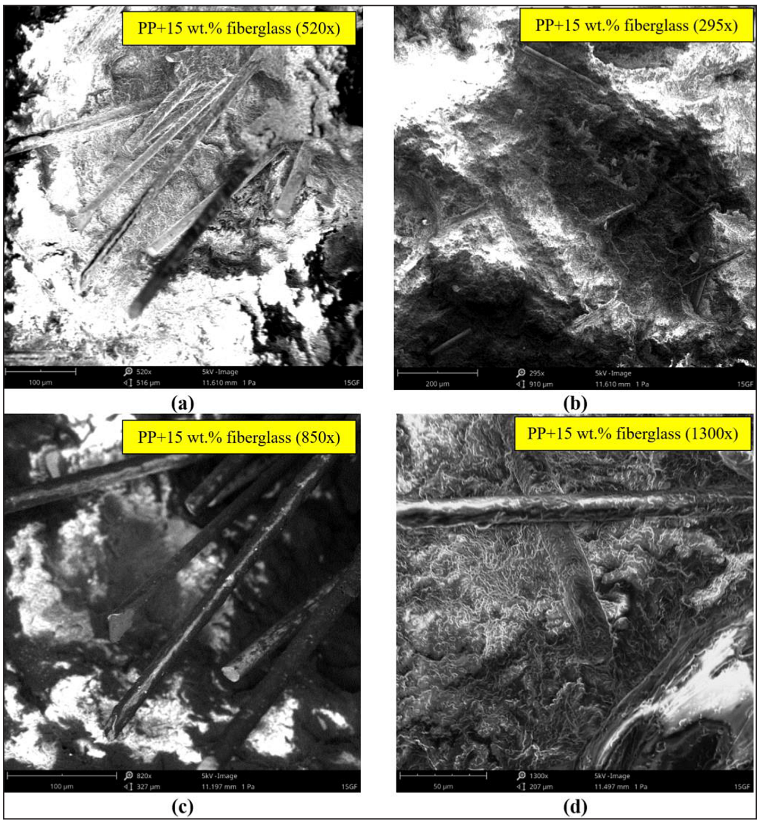

Figure 8. Microstructure of PP + 15 wt.% glass fibre reinforcement at different zooms (a) 520x, (b) 295x, (c) 850x, and (d) 1300x

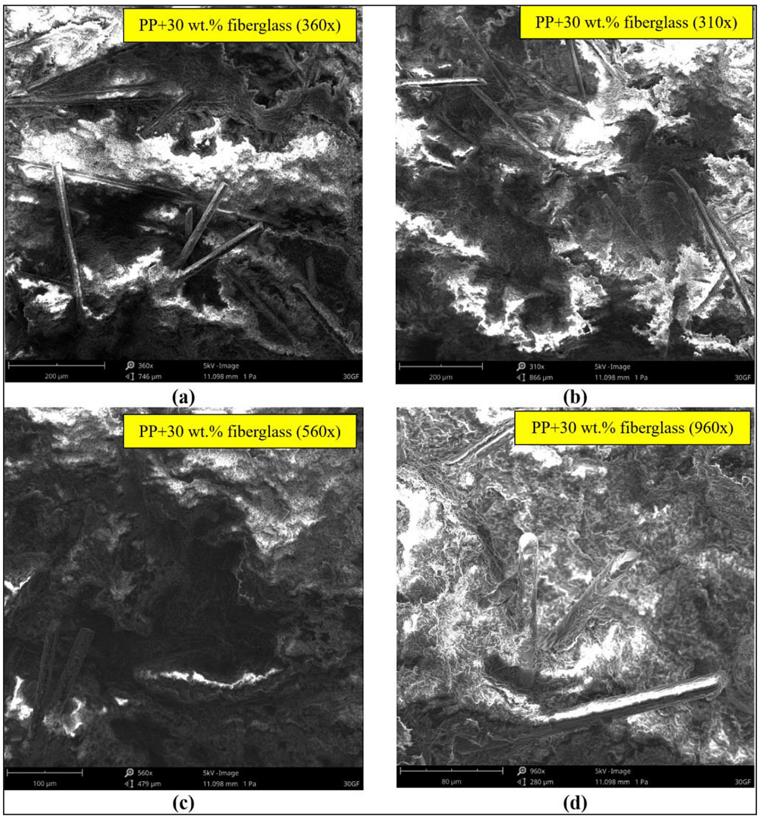

Figure 9. Microstructure of PP + 40 wt.% glass fibre reinforcement at different zooms (a) 360x), (b) 310x, (c) 560x, and (d) 960x

Effect of glass fibre percentage ratio on cracks locations

Regarding the macroscopic analysis of cracks, it was observed that the front side manhole cover variants with filler were damaged similarly with both considered contents. Unlike the variant with the same geometry made of pure polypropylene, the covers with glass fibre reinforcement did not crack on the front surface in any of the tests, on which both in the case of the 15 wt.% glass fibre variant (Figure 10a) and the 30 wt.% (Figure 10b) showed no signs of destruction. Observations of the back side of the covers showed that the circumferential rib was cracked in several locations in the vast majority of cases with additional radial stiffening ribs (Figures 10 c and d), which, as previously shown, is the effect of stress concentration by these additional ribs [29]. It was also shown that in the variants considered, cracking occurred in many positions of the internal circumferential rib (Figure 10 e and f) in cover core region, and surface cracks were observed in the central area of the covers. Cracking on the outer circumference of the cover is a phenomenon that only occurs in the variant with 15 wt.% fibrous reinforcement content.

Effect of radial steel bars ribs

Figure 11 provides a summary of the curves obtained during compression tests of various cover variants, including those with additional radial ribs and those with the same geometry but an

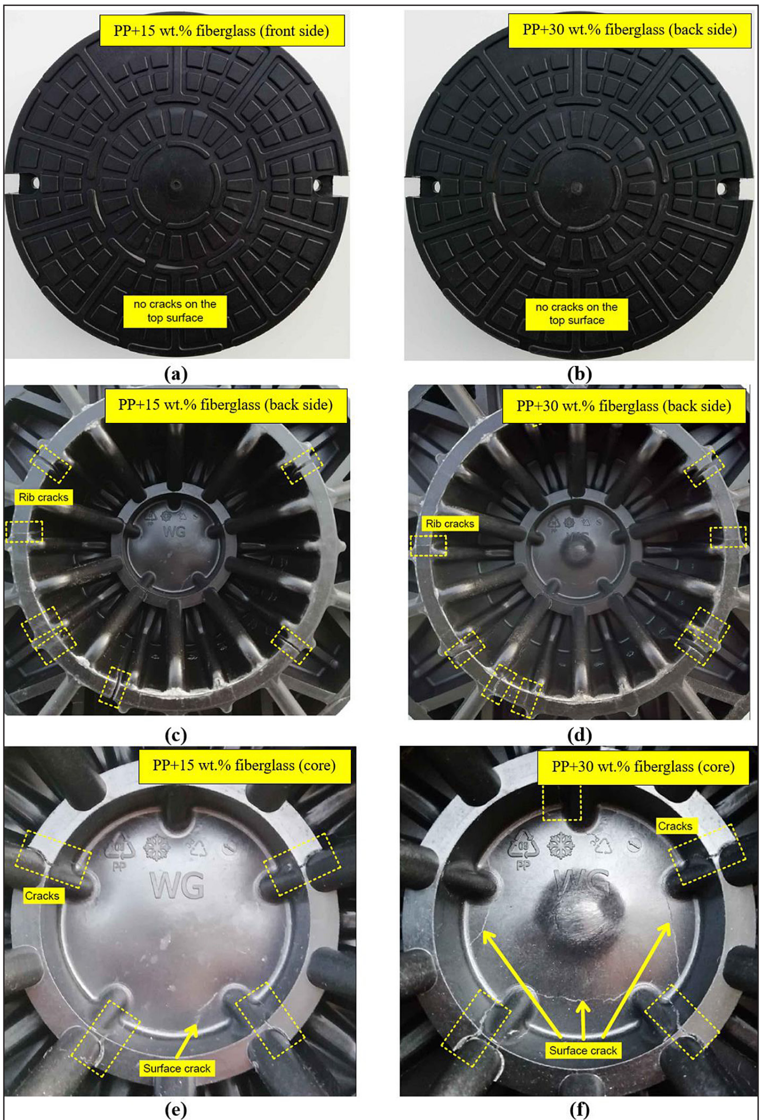

Figure 10. Crack's locations (a) front side (15% wt. glass fibre), (b) front side (30% wt. glass fibre), (c) back side (15% wt. glass fibre), (d) back side (30% wt. glass fibre), (e) core (15% wt. glass fibre), and (f) core (30% wt. glass fibre)

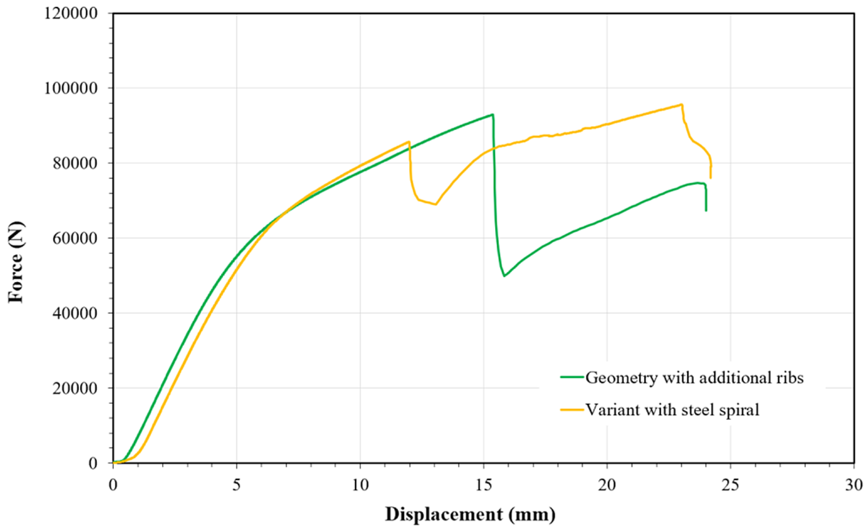

Figure 11. Effect of steel radial ribs on manhole cover compared with fibre glass reinforced cover according to force-displacement curves

additional spiral steel bar. The covers functioned similarly during the initial loading phase, showing no significant differences in stiffness. However, during the tests for the variants with a spiral, the phenomenon of tearing was observed in the plastic area surrounding the steel rod, which means that the interaction between the steel reinforcement and the surrounding plastic material plays a significant role in the overall load-bearing capacity. The result was a significant reduction in the cross-sectional area of the circumferential rib, leading to cracking with an average force value of 86.21 kN (SD = 1.06 kN). This was lower than the load capacity of the variant without a bar, which was 91.82 kN (SD = 0.82 kN). However,

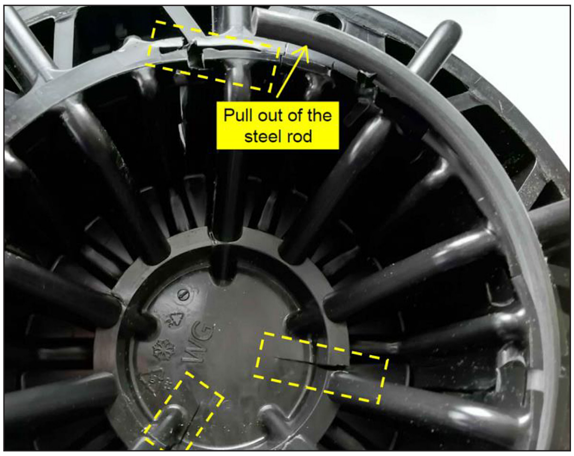

Figure 12. Crack locations in the case of adding a steel radial rib

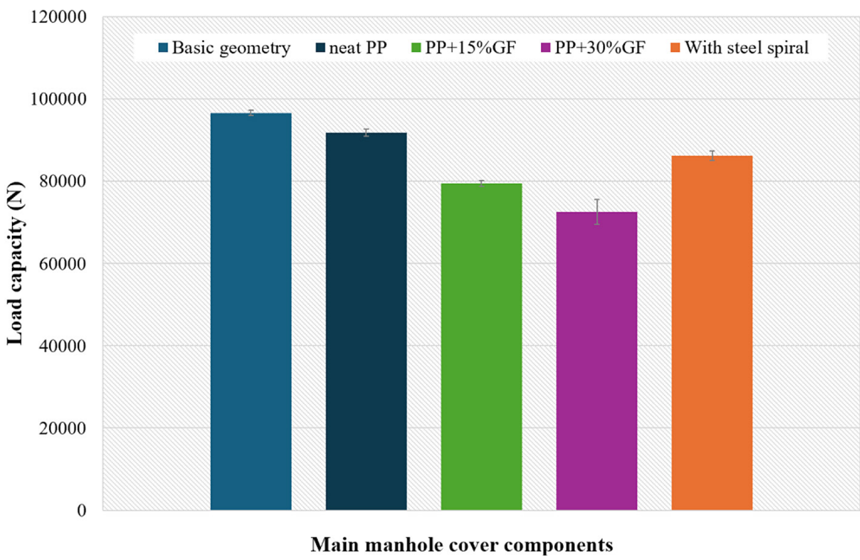

Figure 13. Effect of main manhole cover components on the load capacity

unlike the second variant, with a further increase in the cover deformation, the force increased to a higher value, i.e., an average of 97.35 (SD = 3.6 kN). It indicates that the rod is located too close to the lower surface of the edge; the negligible adhesion forces between the steel rod and the polypropylene material with sufficient deformation result in the tearing of the rod with significantly greater stiffness than the material, as shown in Figure 12.

A steel bar in the form of a spiral, intended to act as a reinforcement, was used in this form because the costs associated with introducing this reinforcement were considered to be relatively low. Although an alternative was considered a closed ring made of a rod, the ends of which would be welded, it was considered too expensive a solution for a low-cost product. Figure 13, which includes all the load values at which failure occurred and the standard deviation values for all cases, generally summarises the results. To sum up, the research showed that the measures taken to improve the load-bearing capacity of manhole covers do not lead to the desired effect. The work aimed to indicate the reasons for reduced load-bearing capacity during subsequent attempts to strengthen the cover.

CONCLUSIONS

This study investigated the possibility of strengthening polypropylene manhole covers with ribs to increase their load-bearing capacity. The strengthening was carried out in two stages, the first by forming ribs by injecting a certain percentage (15 wt.% and 30 wt.%) of glass fibres and in the subsequent stage, a spiral steel bar was added in a circular shape to the cover. The most important conclusions that were noted:

The results of the first stage showed that both percentages added to form the reinforcement ribs did not perform better than the covers made of pure PP; in the case of adding 15 wt.%, the results showed an average decrease of 12.36 kN in the cover load capacity. In the case of 30 wt.%, the capacity load bearing decreased until it reached 19.31 kN.

The results show different fracture surface areas of the cover with 15 wt.% fiberglass content, and the observations of the selected area reveal a non-uniform distribution of fibres in the material volume, with significant fibre clusters visible.

During the injection process, the dominant direction of the fibres aligns with the direction of the material flow, creating a cylindrical-shaped rib in the axial direction. Thus, no broken fibres that would be stretched during loading were observed at the fractures.

The addition of the spiral steel rod significantly decreased the cross-sectional area of the circumferential rib, which in turn caused cracking with an average force value of 86.21 kN, less than the 91.82 kN load capacity of the variant without a bar.

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