ANALYSIS AND DESIGN OF A NOVEL HEAVY-DUTY PRECAST ELEMENT

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ABSTRACT: Window sills are common to most buildings. In Ireland, concrete is the most popular material used for external sills. A standard one-metre concrete window sill weighs about 70kg. While external window sills are required to have sufficient capacity to resist damage during transportation and loading, they are non-structural elements. Therefore, there is no need for their high self-weight. This project looks to redesign concrete window sills to make them lighter. Decreasing the amount of concrete used in each sill would significantly reduce their self-weight. This would make concrete window sills more manageable in terms of transportation and installation.

Two design concepts were developed and tested. One concept sees the removal of concrete through the central plane of the sill. This effectively makes the sill hollow, reducing the self-weight by up to 30%. The other concept sees the removal of concrete from the under-side of the sill. This reduces the self-weight of the sill by up to 45%. Fibre reinforcement was introduced to both concepts to improve the flexural strength of the concrete elements. The concept sills were tested against solid reinforced concrete sills to compare their resistance to failure due to cracking.

KEY WORDS: Concrete; Fibre reinforcement; Fibre reinforced concrete; FRC; Precast concrete; Window sills; Weight reduction.

1 INTRODUCTION

Window sills are a common component in a building. They are installed beneath most windows. The main purpose of the sill is to draw water away from the brickwork during wet weather. To achieve this, they are designed and manufactured with a sloped top surface and a small indent on the base. During construction, window sills help to hold the window in place. They ensure the window is lined up properly with the cavity of the building. Window sills are a non-structural element. They do not support load from the window or the walls above.

The most common material used for sill manufacture in Ireland and the UK is precast concrete. In Ireland, the width of sills can range from 220-460mm. The front face of the sills are typically 100mm, though 50mm front faces are also common. Window sill lengths typically range from 600mm to 2700mm. Longer lengths can be manufactured on request.

Concrete is a dense material with high self-weight. This causes difficulty during installation as it must be carried and positioned manually. The maximum recommended lifting weight is 25kg for a male and 16kg for a female [1]. Therefore, the excessive weight of the sills could negatively impact the welfare of workers. Difficulties arise when lifting sills or carrying them over uneven surfaces. A 2009 report by Hunter and Leah found that manual handling triggered 34.1% of non-fatal accidents in the Irish Construction industry [2]. In 2017, a report by the Health and Safety Authority (HSA) concluded that manual handling triggered 32% of non-fatal accidents [3].

The objective of this project is to design relatively lighter concrete sills that could be manufactured without incurring excessive expense or significantly weakening the element. This report focuses on standard 100mm face sills. Testing was conducted to compare the new designs with existing precast concrete sills.

The authors approached several precast concrete manufacturers while researching this project. One supplier, Moylough Concrete Products, offered to supply the authors with concrete sills for testing purposes. The company also supplied concrete cubes and cylinders to determine the characteristic compressive strength and flexural strength of their precast concrete mix.

2 DESIGN CONCEPTS

Two different design concepts were developed for the purposes of this project. They were referred to as 'Void Sill' and 'Hollow Sill'. Each of the concepts were cast using fibre reinforced concrete (FRC) in the NUIG Concrete Laboratory.

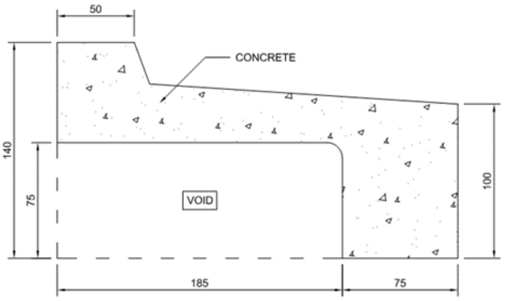

Figure 1. Void sill concept.

2.1 Void Sill

For this concept, the cross section of the sill has been adjusted, with a 75mm x 185mm portion of concrete being removed from the underside of the sill, Figure 1. For manufacturing purposes, a fill material, such as timber or insulation, would be used to create the void. This achieves a weight reduction of approximately 45%.

During installation of the sill, it could either sit directly on the blockwork or a spacer could be placed in between the sill and the blockwork. In storage, a sill is left on a pallet until it is ready for delivery. It will not be under any external loadings or vibrations, bar gravity. A piece of 3-inch timber, or a similar shape altered to suit, could replace the concrete of the 'void' section. This would be sufficient to support the visible concrete section.

During transportation, a re-usable element would be clamped to the visible section. The sill could also be wrapped in packaging to keep it safe during transport. Existing moulds would need small alterations to create the 'Void' sill. No extra machinery would be required in the construction of this sill.

A drawback of this concept is that the potential reduction of its capacity to resist failure could make the sill impractical in the real world. It may not be able to arrive on site undamaged and would have a greater vulnerability to impact at long lengths. To remove the amount of concrete intended, the depth of the sill would have to be reduced from 100mm to just over 30mm at its narrowest point. It would require FRC, as the inclusion of rebar may not be possible due to a lack of cover at the narrowest point in the reduced cross-section.

2.2 Hollow Sill

The idea for this concept is that the sill would be hollowed out through the middle plane, Figure 2. The cross-sectional dimensions of the sill would remain unchanged, but the internal concrete would be removed.

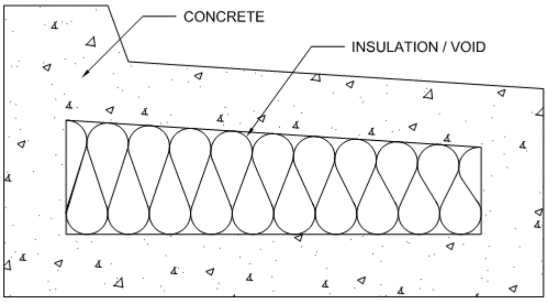

Figure 2. Hollow sill concept.

There are two main options regarding the hollowed space. It could either be left empty or filled with an alternative material. The material cost of making this concept would be less if it were left empty. It may be beneficial to fill the hollow with insulation as it would reduce the effect of cold-bridging and would provide extra support to the thin concrete element.

The Hollow Sill concept would achieve a 30% weight reduction. Bricklayers would be familiar with the installation of this sill as the outer perimeter would not change. The installation process would be similar and easier due to its relative lightness. It also has an advantage over the Void Concept as it does not require an attachable element to aid its strength.

It is expected to have a decrease in strength. It shouldn't be as significant as the 'Void' sill. A reduction in strength is expected with a reduction in cross-section. The 'Hollow' sill would have more mass and a more rigid section. It should have better resistance to cracking than the 'Void' sill.

The main concern with this concept, however, is simply if it can be mass produced in practice. The fact that the removal of the concrete does not occur at an exposed surface adds to the difficulty of producing this 'Hollow' sill. A precast manufacturer would require new moulds to manufacture this concept sill.

3 MATERIALS AND METHOD

Moylough Concrete Products provided three 1050mm length, 100mm face window sills for testing. These window sills were tested using a basic three-point test, where a load was applied at mid-span until failure. The displacement experienced was also recorded. Moylough Concrete also provided three 150mm concrete cubes and three 100 x 100 x 500mm mini beams. All concrete elements were formed from the same batch of concrete. The cubes were crushed to determine the compressive strength of Moylough's mix. The beams were tested to determine the flexural strength.

A batch of FRC was mixed in the NUIG Concrete Laboratory. Fibres were introduced to increase the flexural strength of the concrete, as thin concrete elements were being formed. Plywood moulds were assembled to allow for the formation of two Hollow sills and two Void sills. Insulative material was used to create the hollow in the Hollow Sill and the void in the Void Sill, see Section 3.1.4. Three 150mm cubes and three 100 x 100 x 500mm beams were also formed from this FRC batch. All FRC elements were tested in the same manner as the concrete elements provided by Moylough Concrete, for comparative purposes. These tests helped to highlight the discrepancies in flexural and compressive strengths between the two concrete batches.

This project aimed to replicate the design mix provided by Moylough Concrete. It was hoped that direct comparisons could be made between the Moylough and FRC sills. However, the FRC mix had to be adjusted to achieve the desired workability. This resulted in a lower strength concrete being formed.

3.1 Materials

3.1.1 Moulds

Shuttering plywood, 19mm thick, was used as formwork for the window sills. Mould oil was applied to the formwork to create a barrier between the concrete and the formwork, allowing for easy removal of plywood once the sills have set. The cross sections of the moulds were matched to stop-ends received from Moylough Concrete. Four moulds were formed, two for each of the Hollow sills and Void sills.

3.1.2 Concrete Mix

Moylough Concrete use a C40/50 design mix for their sills. Table 1 shows the material weights used in Moylough's mix. This mix achieves a W/C ratio of 0.35. The volume of water used in Moylough's mix is weather dependent, as their coarse aggregates are stored outdoors. Therefore, they will have a higher water content after wet weather conditions. The water used in the mix must be adjusted accordingly. Moylough use Quinn CEM II/A-L 42.5N Premium Grade Cement.

Table 1. Moylough Concrete design mix.

Component	Description	Mass (kg/m^3)
Coarse aggregate	4/10mm washed chips	1180
Fine aggregate	3mm washed sand	800
Cement	Quinn CEM II/A-L 42.5N	450
Water	-	160

Table 2 shows the material weights used for the FRC mix. The W:C ratio for this mix is 0.42. This higher W:C ratio is indicative of a lower strength concrete.

Table 2. FRC design mix.

Component	Description	Mass (kg/m^3)
Coarse aggregate	4/10mm washed chips	1225
Fine aggregate	3mm washed sand	835
Cement	Quinn CEM II/A-L 42.5N	515
Water	-	215
Fibre reinforcement	GCP STRUX® 90/40	0.49

3.1.3 *Fibre Reinforcement*

The FRC mix was designed by the authors based on Moylough's mix. Adjustments had to be made to allow for the addition of fibre reinforcement. Moylough Concrete supplied the authors with reinforcing fibres. The macro-fibres were STRUX® 90/40 produced by Grace Construction Products (GCP). The dosing rate for these fibres was determined from technical information received from GCP Applied Technology.

3.1.4 *Insulation Material*

The material used for the hollow and void regions of the sills was DOW XENERGY^{TM}LBH 300kPa XPS High-density polyethylene (HDPE) Insulation. This material is relatively dense and has a much lower self-weight than concrete. It is typically found in structural insulation panels. The material was sourced from SIP Energy Structural Insulated Panels through NUIG.

3.2 *Method*

3.2.1 *Preparation of Concrete Moulds*

The section of insulation used to replace concrete in the void sill had to be held in place. Otherwise, the material would rise as concrete was poured into the mould. Timber laths were attached to the insulation for the Void sills. During the pour, the laths could be screwed to the moulds to hold the insulation in place, Figure 3.

A 30mm section of timber was attached to the underside of the laths used for the Hollow sills. These laths were to be secured at mid-point in the mould after the insulation was placed, Figure 3. The 30mm piece of timber would reduce the possibility of the hollow insulation rising during the pour.

An initial pour line (IPM) was drawn on the moulds. The IPM indicates the level at which the concrete was to be poured before placing the HDPE insulation. The insulation was secured at numerous points along the side of the mould using screws.

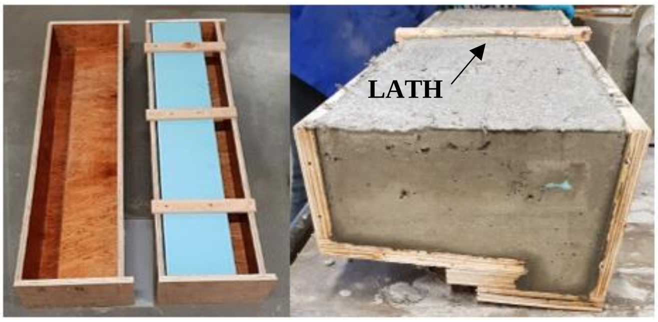

Figure 3. Void sill mould with timber laths and Hollow sill mould being stripped.

3.2.2 *Fibre Reinforced Concrete Batching*

One batch of FRC was produced using a Crete Angle model 'M' mixer. This batch was used to create two 1050mm Hollow sills, two 1050mm Void sills, three 100 x 100 x 500mm beams and three 150mm cubes.

The aggregates were dry mixed for one minute before a bag of cement and 10kg of water were added to the mix. The mixer was powered on for another minute. The remaining cement was then added to the mixer with 10kg of water. The mixer was switched on again and handfuls of fibres added. The fibres were separated to ensure minimal fibre balling. Fibre balling occurs if adequate mixing is not provided. Balls of fibres form within the concrete, producing weak points or voids in the element [4]. Water was added in 1kg increments to ensure sufficient workability.

3.2.3 *Pouring of Sills*

Each mould was place individually on the vibrating table. Concrete was trowelled into the mould and the table's vibrating mechanism started. The vibrations remove air from the concrete, compacting it. All corners of the mould were tamped using steel rods. This guarantees complete filling. Once the concrete was filled to the IPM, the insulation was put in place and secured. The remainder of the mould was then filled while being vibrated and tamped. The vibrating mechanism was stopped and the concrete at the top of the mould smoothed-off using a trowel. The mould was then removed from the table and placed in storage to set. A similar method was used to produce the cube and beams.

The sills were left in storage for 24 hours before being stripped. The side panels were un-screwed and removed carefully using a hammer and chisel. The cubes and beams were also removed from the moulds. All concrete elements were placed in a 2m x 1m curing tank until testing. The water in the curing tank was kept at 20°C [5].

3.2.4 *Moylough Concrete Window Sill Testing*

The three sills obtained from Moylough Concrete weighed ≃70kg each. The sills were cast with three 6mm steel reinforcement bars. All Moylough sills were tested at an age of 49 days using a Zwick 250kN actuator. From a design perspective, concrete is at full strength after 28 days [6]. The sills were placed on two steel I-beams supports. A timber wedge was cut in an inverted manner to the top face of the window sills and placed at midspan of the sill. This ensured the load was being applied across the entire top surface, Figure 4.

The first sill was tested at a loading rate of 40mm/sec due to human error. The remaining sills were tested under a loading rate of 0.025mm/sec. Load and displacement was recorded by the machine.

Figure 4. Sill testing.

3.2.5 Moylough Concrete and FRC Cube Testing – Compressive Strength Tests

The Moylough cubes were tested at 7 and 28 days. The spare cube was tested the same day as the sills, Day 49. This gives an indication of the compressive strength of the concrete on testing day. The cubes were removed from the curing tank, dried and weighed. Each was then placed in the Matest Cyber-Plus Evolution model C109N crushing machine A load was applied at a loading rate of 0.6MPa/sec until failure occurred. The results of the test were recorded.

The three cubes made from FRC were tested in the same manner. The compressive strength of FRC could be calculated and compared to the strength of the Moylough Concrete cubes.

3.2.6 Moylough Concrete and FRC Mini-Beam Testing – Flexural Strength Tests

Moylough Concrete Ltd. provided three 100 x 100 x 500mm mini beams to allow the flexural strength of their concrete mix to be determined. Each beam was tested in the 30kN Denison test frame in the NUIG Concrete Laboratory. This is a 4-point test where a transducer applies a load through two points at the top of the mini beam. The beam is simply supported underneath at two points. The load is applied at a rate of 0.04MPa/sec, increasing until failure. Flexural strength, a measure of bending resistance, is determined by:

$$Flexural\ Strength, f = \frac{6M}{bh^2} \tag{1}$$

The maximum applied load was recorded, and the flexural strength of the concrete calculated.

3.2.7 Hollow and Void Window Sill Testing

All sills were removed from the curing tank and weighed. The Hollow sills were tested using the same procedure as the Moylough Concrete sill tests, Section 3.2.4. Due to their flat underside they could be placed directly to the steel supports. At the first point of failure, there were no visible signs of failure. Further loading was applied until a crack was clearly visible in the sill.

The HDPE at each end of the Void sills were removed using a handsaw, hammer and chisel, Figure 5. It was likely that the HDPE would compress under loading causing the sill to rotate. Two timber wedges, 75mm in height, were cut to put in place of the removed HDPE. The sills were then placed on the steel supports with the timber wedges underneath, Figure 5. The hollow sills were tested using the same procedure as the Moylough Concrete sill tests, Section 3.2.4.

Figure 5. Void sill pre-testing.

4 RESULTS AND DISCUSSION

The results from testing the FRC mini beams were compared against the sills supplied by Moylough Concrete. This indicated the increase in flexural strength due to the addition of fibre reinforcement. The cube tests from both batches were analysed to note any discrepancies between the compressive strength of each batch. These discrepancies may impact the mini-beam results. There is likely to be a discrepancy as the FRC batch had to be altered to account for the addition of fibres. The two sets of FRC sills were compared against Moylough Concrete sills to indicate their relative ability to resist failure due to cracking.

4.1 Results from Cube Testing

The Moylough Concrete cubes achieved a maximum compressive strength of 61.2MPa after 49 days. The maximum compressive strength achieved by the FRC cubes is 48MPa. The compressive strength of Moylough's concrete is 27.5% greater than the FRC. This difference in compressive strength affects the interpretation of the mini-beam tests. It would be ideal to compare the change in flexural strength between the two samples solely due to an addition of fibre reinforcement. This cannot be achieved in this project because of the additional variable of compressive strength. Figure 6 shows the results of the cube tests. It clearly shows the disparity of compressive strength between the two sets of cubes.

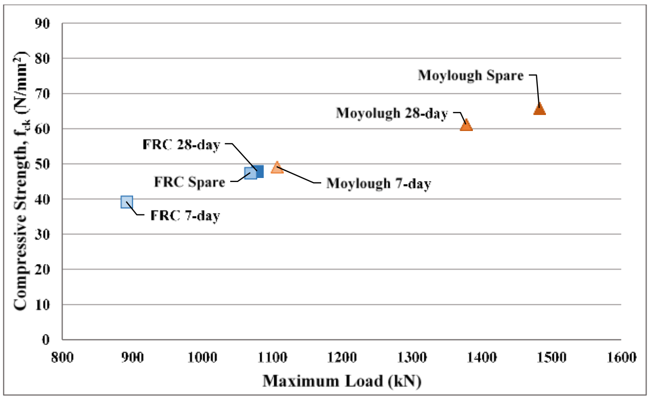

Figure 6. Moylough Concrete and FRC cube test results.

4.2 *Results from Mini-Beam Testing*

Due to malfunction of the 30kN Denison test frame, the Moylough Concrete mini-beams, labelled MCB1 to MCB3, were unable to be tested until 88 days after being batched. The FRC mini-beams, labelled FRCB1 to FRCB3, were tested after 29 days. The average flexural strength of the FRC mini beams was 6.7MPa. The results of the mini-beam tests are shown in Table 3. Whilst there was a gap of almost two months between testing of the two sets of mini beams, the difference in strength was not expected to be substantial.

The flexural strength of the FRC mini-beams was less than that of the Moylough Concrete mini-beams, despite the addition of fibres. However, the FRC mix was weaker than the Moylough Concrete mix. The relationship between a change in flexural strength resulting from a change of compressive strength is unknown. It would be improper to assume that there is a direct, linear relationship.

Table 3. Moylough Concrete and FRC mini-beam flexural tests.

Mini-beam No.	Maximum Load (kN)	Maximum Strength (MPa)
MCB1	15.714	7.071
MCB2	16.745	7.535
MCB3	16.024	7.211
FRCB1	15.002	6.751
FRCB2	14.732	6.629
FRCB3	14.979	6.740

There is an 8% difference between the flexural strength of the two batches. A rough indication of the relationship of the change in flexural strength of a sill due to altering the cross-section can be ascertained due to the similarity of the flexural strengths. A more accurate relationship could be deduced with a greater sample size and less variation in concrete strength.

4.3 *Results from Window Sill Testing*

Three Moylough Concrete window sills, labelled M1 to M3, were tested 57 days after being batched. Each had a weight of ≃70kg. Table 4 shows that M1 did not carry as much load as M2 or M3. This is because M1 was subjected to a much faster loading rate of 40mm/sec in error. The other sills were subjected to a loading rate of 0.025mm/sec.

Table 4. Moylough Concrete window sill tests.

Window Sill	M1	M2	M3
Maximum Load (kN)	10.28	14.83	15.77
Maximum Displacement (mm)	40.80	38.34	38.45

The FRC widow sills were tested 36 days after being batched. The Hollow sills are identified as H1 and H2 while the Void sills are identified as V1 and V2. Table 5 shows the load resisted and displacement of each sill. Figure 9 shows the weights of the sills.

Table 5. FRC window sill tests.

Window Sill	H1	H2	V1	V2
Maximum Load (kN)	10.36	9.76	5.18	8.53
Max. Displacement (mm)	2.22	16.04	10.44	7.03

The maximum load of 8.53kN for V2 is not an appropriate value to use when comparing the two sets of sills. For every other sill, cracking appeared on the surface after the sill was applied with its maximum load. Load continued to be applied to these sills after cracks appeared, though it never became greater than the maximum load. This was not the case for V2. Cracks started to appear on the surface just after a load of 4.24kN was applied, with a maximum load of 8.53kN resisted.

One reason for this unusual behaviour is that the insulation for the void had chipboard attached. This may have contributed to its ability to resist greater load. After testing, it was also discovered that the chipboard was resting on the support, Figure 7.

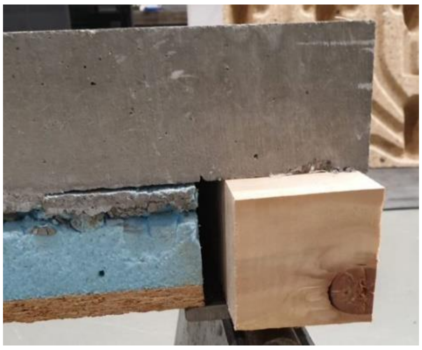

Figure 7. V2 sill after testing.

Sill M1 is not considered in the comparison between the Moylough Concrete sills and the FRC sills. The inclusion of M1 would make the results of the developed concept ideas seem incorrectly more flattering. Furthermore, the maximum load of V2 before cracking occurred, 4.24kN, is used in the comparison. Figure 8 shows the maximum load experienced by each sill.

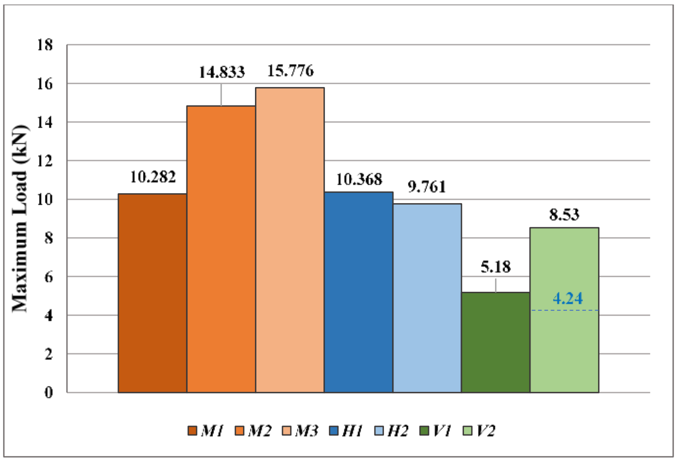

Figure 8. Window sill maximum load.

On average, the Moylough Concrete sills withstood a load of 15.3kN, the Hollow sills withstood 10.1kN and the Void sills withstood 4.7kN. The Hollow sills achieved 66% of the performance of the Moylough Concrete sills and the Void sills achieved 30%. This indicates that the concept sills have a greater susceptibility to failure. A greater sample size is required to yield more conclusive results.

4.4 Weight Reduction

Figure 9 displays the weight of all the sills tested. The Void sills, including insulation, achieved a 43% weight reduction, which is near to the 45% reduction expected. This expected reduction does not account for the weight of the insulation. The Hollow sills achieved a weight reduction of 24%, which is short of the expected 30% reduction.

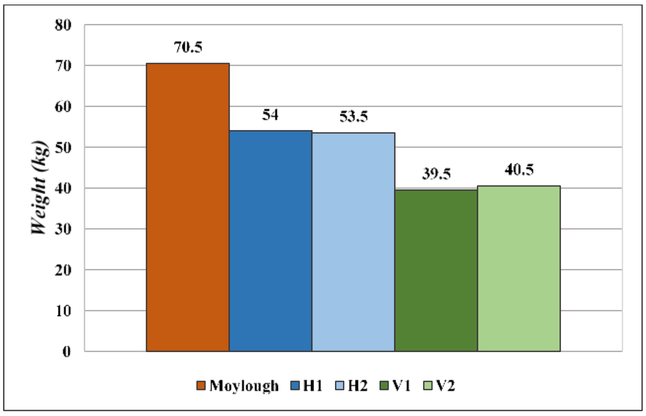

Figure 9. Window sill weights.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- Standard concrete window sills with a 100mm face weigh about 70kg per metre length. This weight exceeds the recommended lifting weight.
- Test results indicated that "light-weight" sills can be produced. The Hollow sill and Void sill achieved a weight reduction of 24% and 43% respectively.
- However, these concept sills were more susceptible to failure. The Hollow sill had a flexural strength equivalent to 66% of a standard sill, while the Void sill only had 30% of the flexural strength of a standard sill.
- The test results were non-conclusive due to a sample size of two for each set of sills. The mix designs for the standard sills and the concept sills differed. Therefore, no direct comparison could be made.

5.2 Recommendations

Further testing is required if "light-weight" concrete sills are to be mass produced. There are several avenues of research that could be further explored regarding the feasibility of reducing the weight of precast concrete window sills, including:

- The addition of fibre reinforcement to increase the flexural strength of the concrete. Micro-fibres added to a concrete mix reduce shrinkage cracking and increase the ductility of hardened concrete. They could aid concrete window sills in resisting damage [7]. Macro-fibres added to a concrete mix improve concrete's flexural and tensile strength and its toughness [8]. Macro-fibres can be used instead of steel reinforcement.
- Further development of the Hollow concept idea. Finite element models and more extensive experimental testing would aid in determining the optimum amount of concrete for a Hollow sill. A process of manufacturing this sill needs to be considered before exploring any attempts to perfect this concept idea.
- Further development of the Void concept idea. Though the dimensions of this sill are constrained by the size of bricks and the way sills are currently installed, testing indicates that this sill is particularly susceptible to damage. Though not exclusive to this concept idea, supporting concrete window sills in transport is a beneficial avenue of research.
- Further investigation into the potential use of lightweight aggregates. One could distinguish the weight reduction brought about simply by swapping the coarse aggregates in concrete with lightweight aggregates. More broadly, a clearer relationship between the change in flexural strength brought about by using lightweight aggregates for concrete elements with the same compressive performance could be deduced. Great difficulty is expected with any attempts to deduce this relationship because of the heterogeneous nature of concrete.

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