An Analysis of the Improvement of a Slate Debris (Deffun) Roof Properties with the Addition of Different Additives

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Abstract: Finding the right balance between retaining certain traditions present in a traditional building and providing great comfort to reach today’s standards and expectations can be challenging. The slate debris (deffun) roofing system is a topic to question regarding this matter, as the present situation allows for this mortar to be removed or covered completely due to the excessive maintenance it requires, as well as its ability to easily form cracks and allow water to penetrate through. This paper focuses on incorporating four different additives (polypropylene fibre, glass powder, cactus juice and kaolin clay powder) to a slate debris mortar’s mixture to improve the performance of this mortar, focusing on water retention improvement, while keeping aesthetic features present in these traditional buildings.

A quantitative approach was used, and two experimental procedures were carried out; a water absorption test, which was held under laboratory conditions, and a homemade setup experiment tested for water absorption and water run-off upon different inclination setups. Regression analysis together with statistical analysis was used to determine whether there is a statistical difference when additives are included with the mix or not. Results have shown that all four different mixes improve the water absorption of the slate debris with polypropylene fibre mix performing the best. There was no statistical difference between the water run-off results through the assembled models, but these results indicated why slate debris roofing is constructed with a high inclination.

Keywords: Slate debris (deffun) mortar, traditional feature, high maintenance, water retention, improvement additives, water absorption

The Concept

Cultural heritage is a legacy of certain processes or artefacts, that have been inherited from one generation to another, and that should be maintained for the beneficial knowledge of the future generation. Cultural heritage not only includes tangible cultures, such as monuments, books, artefacts, and buildings, but also intangible traditions, for example, oral traditions, which are traditions or techniques that have been inherited orally. It is of utmost importance to try and preserve certain elements as these contribute to keeping traditional knowledge and local identities alive.

The slate debris mortar is one of these features that have the right to be restored over time. Although this acts as a tangible element, it can also be considered intangible since its technique has been run down by word of mouth throughout different generations. Being used locally as a waterproofing mortar since the Roman dominion, this mortar consists of ground pottery fragments, slaked lime, and water. This concept was mainly incorporated as a top layer for a roofing structure to discard the passage of water through the other layers that would potentially cause harm to the whole structure. Due to lime not being the best
of binding agents and its fragile state, this roofing element requires excessive maintenance and looking after, and due to the introduction of modern engineered materials locally, Portland cement, this technique has been discarded ever since.

The Research Question

The main intention behind this study was to minimise the maintenance required for a slate debris mortar roofing system and try to prolong its time-lapse with the incorporation of additives that in nature can increase water retention abilities.

Currently, due to excess maintenance, the practice is of either having the slate debris mortar layer discarded, or the layer is covered with modern technical elements, such as liquid sealants, membrane sheeting and tiles. This study tries to provide yet another alternative option to this, and this is to replace the slate debris mortar layer with a better mix to achieve the comfort of a modern roofing element, which possibly reduces the need for much maintenance, whilst improving its water retention abilities.

The traditional Maltese roofing structure has always been flat as opposed to Northern countries whose houses have a pitched roof. This is mainly since our local wet season is a mild and short one. However, this does not justify that water would not penetrate through the roofing element if left unattended or uncared for. Stagnant water that would be left on the roof would drain through the tiniest of cracks, therefore the importance of waterproofing local roofs needs to be taken seriously. Water ingress could manifest its way into walls, resulting in ceiling stains whilst providing the perfect environment for mould to grow.

Aims and Objectives

The main aim of this research study is to determine the best additive that would potentially decrease the slate debris mortar’s water ingress. This was conducted by using a quantitative approach and analysing data collection of samples and models of slate debris mortar, together with four different additives, that were subjected to different water absorption experiments. However, apart from this, this research would also have a secondary aim, that of determining the best-inclined position for water to slide off the best way possible, whilst ensuring that the slate debris mortar absorbs the least amount of water.

The principal objective for this study would be to hypothesise and verify it by data collection using a quantitative approach. This would therefore become the basis for the whole study, and the hypothesis is as follows:

*Adding additives to a slate debris mortar (deffun) mixture has a positive effect on the water retention abilities.*

Literature Review

Origins

Pottery, as an additive to hydraulic mortars, has been in existence for an extended period. The Romans used it to incorporate pozzolanic additives to hydraulic limes, as these perform a chemical reaction with lime, due to the presence of alumina and silica, which therefore produces durability to the mortar (Taylor 1997).
The exact period relating to the introduction of the use of pottery and mortar in Malta is still unknown. However, before the Roman dominion (around the year 218 BC), Malta was under the Phoenicians and the Carthaginians (circa 550 BC) (Savona-Ventura 1997). As documented by Buhagiar (1996), Phoenicians and Carthaginians believed in the same gods. In Malta, they have dedicated a sanctuary for their god named ‘Astarte’ and renovated this sanctuary, better known as Tas-Silg. This sanctuary holds some traces of slate debris: “The courtyard was paved with flagstones while the colonnaded walk had a floor of reddish cement compound of crushed pottery sherds and lime...” (Buhagiar, 1996, p.7).

This means that from when the Romans invaded Malta, the concept of mixing crushed pottery with lime was already being used. Later, the Romans fostered this technique as can be seen in the flooring of the Roman Domus, Rabat. As documented by Chetcuti (2006) during restoration works in the Roman Domus, a large cistern was found to be rendered with pottery fragments.

Although the introduction of Portland Cement in the 1950s lessened the use of the technique of mixing pottery with lime, a gap in the literature exists which motived the aims behind this study.

Slate Debris (Deffun) and Mortar

The word deffun is defined as crushed pottery on its own. However, locally the word refers to the actual lime mortar mixture. The slate debris (deffun) lime mortar is composed of lime, which acts as the binder, crushed pottery (aggregates), and water (Chetcuti 2003). Lime (calcium carbonate CaCO₃) is produced from burning limestone in very high temperatures, and when it is combined with water a lime mortar paste is produced. This paste has adequate water retention abilities and plasticity; however, it lacks in strength (Snow & Torney 2014).

Mortar is defined as a cluster composed of fine particles bonded together by a binding agent that can be identified as having a plastic consistency which can easily be trowelled, and once dried in place, it becomes a hardened material. Mortar can be classified depending on the binder used; lime-based mortar (lime being the binding agent) or cement-based mortar (cement being the binding agent) (Ngoma 2009).

Uses for a slate debris mortar

Our ancestors believed in the importance of the collection of rainwater, therefore the incorporation of the crushed pottery technique gained more popularity through time. This concept was mostly incorporated on the top layer of a roof structure for the protection towards rainwater and water catchment (Chetcuti 2003). The slate debris mortar was not only used for roof protection, but also for re-pointing open joints, on top of parapet walls, on churches’ domes and roofs, on a timber Maltese balcony roofing structure, and to cover water sprouts to repel water.

It was brought to the researcher’s attention that due to the memorial use of the slate debris mortar and its characteristically red colour, it has become a tradition to paint the roof structure of a traditional balcony in red. This bright red colour is referred to as demm il-baqra.

Construction

The construction of a Maltese traditional roofing structure begins with the gathering of broken or unwanted pottery, constituted of broken pieces of pottery pots, vases, plates, and ducts. People who used to do this sort of collection were referred to as id-diffen. To
crush all this pottery, a lower coralline limestone block with a curved bottom surface is used. Coralline limestone was preferred to be used for this process because of the high strength properties it has as a rock. Two holes are present at the right and left sides for better gripping to have control over the movement of the stone. Once the pottery is crushed, it can be referred to as *deffun*. It is then collected into sacks, weighed, and sold (Lanfranco 2003)

The construction of a Maltese traditional roof divides itself into different layers and stages, each of these having an important use, whilst also employing traditional techniques.

*First Layer – Stone Slabs*

Once the walls are constructed, which are normally double skinned walls filled with soil and stone fragments, stone slabs were the first layer to be placed. Stone slabs, approximately having a height of 9cm (3 ½ inches) (Calleja et al. 2001), known as *xorok* were placed on corbelled stones, known as *kileb*. *Kileb* are stone wedges which are used to help widen the width of the room since no concrete or steel reinforcement was used at that time, and the construction of a traditional roof did not allow for a room of a certain size to be possible (Miklem 2019). Before being placed on the stone wedges, stone slabs are cut at one end to create the visuals of widening at one side and narrowing on the other, so when these are placed, they complement each other for better bonding between one another. This is done to ensure safety and to minimise the risk of the structure collapsing should one of these slabs break. Lime mixed with water is used to fill in each divisional section to bond each stone together (Chetcuti 2003).

*Second Layer – Psisa*

The next layer is called the *psisa* consisting of globigerina limestone fragments, having an approximate diameter of 19mm (Calleja et al. 2001). These fragments are placed on the stone slabs and then compressed using a *marżebb*, which is like a wooden hammer and utilised to distribute the material evenly. The total height of the whole layer would approximately be 7.6cm (3 inches) (Calleja et al. 2001). During this stage, one needs to beat cautiously with the hammer as heavy beating could result in breaking the stone slabs in the process (Chetcuti 2003). Afterwards, an earthenware drainpipe is installed leading to the reservoir for the collection of rainwater (Borg 2011).

*Third Layer – Screed*

The screed layer, consisting of powdery fragments of globigerina limestone and sometimes even traces of soil, is then applied. The same process is repeated, and this material is distributed on the *psisa* layer, with water added and compacted once again using the *marżebb*. However, this layer is not distributed evenly, as it needs to form the inclination of the roof to bend towards the waterspout for water catchment (Chetcuti 2003). The slope is constructed by applying more screed on the opposite side of the waterspout and less on its side, forcing water to slide off.

*Slate Debris (Deffun) Layer*

Lime was first soaked in water for several days to obtain a lime putty before one could make use of it. This technique would enable the lime putty to have a plasticity, soft and flexible ability to be moulded easily (Snow & Torney 2014). This was considered as the norm and there are no documented exact measurements of the water-lime ratio, but it was passed from one generation to the other and was calculated differently from one person to another, depending on their experiences and knowledge on the field.
Before the application of the lime putty on the roof, the screed layer is wetted cautiously throughout. It is important not to deposit excessive water as this could temper with the already casted slope since this layer is powdery. The lime putty is then distributed evenly throughout having a thickness of an average between $\frac{1}{2} - \frac{1}{4}$ inch (Calleja et al. 2001). Here, the *marţebba* is used once again to remove the excess water from the putty through beating. This trick of adding water is done to ensure good adhesion between the screed and slate debris layer. The crushed pottery is finally distributed over the whole roof structure, making sure that the edges and area near the waterspouts have abundant amounts. The distribution happens more than once, depending on the voids left without crushed pottery (Chetcuti 2003). Although there is no exact measurement of the ratio between lime and crushed pottery, as this is done differently each time, Calleja et al. (2001) documented that the assumed calculation is that of two parts lime and three parts crushed pottery.

According to Maltese folklore, this last step was mainly done by women called *il-ballata*, where they would spend hours beating on the slate debris mix, sitting on a small stool, to ensure that the mix is compacted well. During these hours, they would start singing Maltese folklore songs together, thus creating a beautiful traditional atmosphere whilst beating on the roof structure according to the rhythm of the folklore song (Mousù 2020). Once the mixture is mixed according to their employer's likings, the women began to smoothen out the surface with a trowel, better known as *il-kazzola*.

**Limitations with Lime Mortars**

Lime mortars have been in existence for many years, as most historic buildings are built with them. These have proven themselves to have high water retention and workability while still in their plastic state and then develop the needed strength over some time. However, with time, buildings begin to develop a decline in their performance, and the main explanation for this is that water can speed up the deterioration of a structure when a crack is developed, allowing for the passing of water (Bindiganavile et al. 2016). Thus, maintenance of any material is important, and it involves regular cleaning and carrying out routine tasks to prolong the lifespan and function of the material (Government of South Australia 2008).

**Crack Formations**

In the past, it was of great importance to keep the slate debris layer relatively moist during the curing process to reduce the development of potential cracks. For this reason, this layer was preferred to be conducted during winter for a slower drying process. However, when works had to be done during a warmer season, a common technique was that of having wet potato sacks or straw distributed on the newly applied roof layer for a slower curing process (Lanfranco 2003).

In a modern concrete roofing structure, once the curing stage is completed; thus, water particles evaporate, this process will leave voids in concrete, allowing for water to easily seep through (Anupoju 2016). Keeping concrete in moisture during the curing stage ensures that the material will cure adequately, thus reaching the desired strength. To minimise this concept, especially during warmer temperatures and to prevent water evaporation from concrete, blanket plastic sheeting is placed all over the roof structure (TRP Ready Mix 2018). This concept can be applied to a slate debris roofing system, whereby instead of using wet potato sacks or straw, modern engineered technologies, proven to be more effective, can be applied to leave this slate debris layer hydrate slowly and reduce cracks.

Due to the local excessive warm climate, cracks develop by time, allowing for water to penetrate through the structure causing unnecessary damages to the whole roofing
structure. Cracks can also develop due to the resting and movement of the whole structure. As a result, this type of roofing system requires excessive maintenance, therefore every year the whole slate debris layer needs to be lime washed. This includes a mix of lime, water and sometimes a red coloured pigment, to fill in the cracks. According to Chetcuti (2003), this technique also helps in filling in gaps where the material has either deteriorated or dissolved through time.

**Plant Growth and Moss**

Plants and moss are other problems that can cause a slate debris roofing system to deteriorate faster. Since soil would sometimes be incorporated in the roofing system, and due to minor cracks allowing for the passage of water, plant growth can occur resulting in major cracking.

Algae and moss are also problematic factors. These tend to grow in shaded and damp areas and can damage the roofing structure as these have the potential to hold water from flowing, allowing for a bigger chance for water to penetrate through the layer (Stodart 2019).

**High Slopes**

It can be assumed that a high slope was formed, with the screed layer, so that water could run off the roofing system as quickly as possible to minimise water absorption by the mortar or water penetration through cracks. Although this high slope can be visible in old buildings constructed prior to the invention of Portland cement, it can be much more visible on the roofing system of churches or chapels.

**Additives**

Any mortar is identified as being durable when the material can withstand the negative effects produced by the environment without causing itself to deteriorate. Our ancestors modified their mortars using abundant materials present at the time, based on observation and experience, but not necessarily due to an understanding of the chemical properties. Materials such as milk, blood, animal hairs and oils were used (Artis 2014).

Water permeability of any material greatly depends on the voids and interconnectivity of pores present within that allow for the passage of water. It has been proven many times that by the addition of certain additives to concrete and mortars, an improvement of water permeability can be obtained. This reduction of water flow through the material occurs because additives decrease internal shrinkage cracks while reducing water flow by decreasing water flow paths within the material itself (Hoseini 2013).

**Glass Powder as an Additive**

For the incorporation of glass powder as a percentage replacement of aggregates in concrete or mortar, studies show that the slump test values were decreased when the glass powder percentage was increased. According to Lu and Ouyang (2017), the workability of mortar was dependent on the size of the glass particle, since the finer the particle is, the more the workability will increase. In their studies, Hamou et al. (2016) concluded that the highest percentage of glass powder to be incorporated in concrete should not exceed 20% to have a high-performance concrete.

Soda-lime silica glass is a widely popular glass because of its workability, being inexpensive and chemically stable, consisting of 70% silica dioxide, 15% sodium oxide, 9% calcium oxide
and traces of other compounds. It is most popular in the manufacturing of glass bottles, light bulbs, and windowpanes (Mahajan 2008). During a study conducted to replace soda-lime glass powder with aggregates, it was established that when the percentage of aggregate replacement exceeded more than 20% there was an increase in water absorption percentage values. This study shows that due to the utilization of soda-lime glass, positive results, such as increase in strength, lower porosity, lower water absorption, and reduction in overall weight are obtained (Islam et al. 2016).

**Polypropylene Fibre as an Additive**

According to various studies conducted, polymers used as additives can enhance the pore structure of any concrete or mortar mixture, and as a result, water absorbed by the mixture is minimised (Borhan & Sutan 2011).

Incorporating fibre particles into concrete has been proven to have many positive results in increasing tensile strength, flexural strength, toughness, compressive strength, and modulus of elasticity. Since concrete is a weak material in tension it becomes prone to cracking, allowing for the passage of moisture causing the concrete to deteriorate. A study was conducted to examine how different percentage volumes of polypropylene fibres affected the mechanical properties of concrete. As a result, it was concluded that by the addition of polypropylene fibres, there was a notable increase in the water absorption percentage when 0.5% of polypropylene fibres were added by volume of concrete (Mohamed 2006).

During restoration works carried out in the tas-Salvatur chapel in Kalkara, where a new slate debris mortar mixture had to be re-applied due to heavy deterioration, the conservational architect incorporated shredded glass fibres in the new mix to produce a better interlocking bond between the previous layer and the slate debris layer, which resulted in increasing the shear capacity and the prevention of mortar shrinkage (Chetcuti 2006).

**Prickly Pear Leaf Juice**

Organic additives have been incorporated in mortar mixes since ancient times to help in the improvement of the durability and working properties of such mixes. The *Opuntia ficus-indica*, more commonly known as *bajtar tax-xewk* is a potential additive to mortar mixes as it is excessively available in warm temperature climates such as Malta and can be very easily harvested. This plant can be identified from its wide, thick, and flat pads covered in segmented stems and spines (Grant 2020).

Each cactus leaf pad has an approximation of 90% water content. In an experiment conducted to replace such juice with water content to be used as an additive to cement, the researchers diced the leaf pads and boiled them, and subsequently the mucilage produced was sieved to remove large particles. The incorporation of cactus leaf juice to mortar showed promising results when added to cement pastes as this enhanced the hardening properties of the samples, where the best percentage replacement was observed to be of 0.5-1% to water (Aquilina et al. 2018).

From research, discussions and encounters made by the researcher, it was made clear that the juice produced by the prickly pear leaf was used for waterproofing walls, as the thickness of the juice allowed this product to act as a waterproofing agent. To obtain this juice, the prickly pear leaf would need to be sliced into small cubes and boiled in water. The water can then be used for waterproofing. Others also stated that the leaf was sliced open, and the juice was scraped with a knife.
Clay as an Additive

Clay has the potential to act as a bonding agent since it has waterproofing properties (Snow & Torney 2014). Kaolin, Bentonite, and Mica are all clays popularly used due to their abundant availability and low price. However, kaolin is an aluminosilicate clay mineral, consisting of alumina and silica plates with a strong connectional bond (Frost & Kristof 2004). This makes kaolin a very stable clay, proven to have the lowest water absorption of all (Rodriguez & Orrego 2015). Kaolin has the potential to be used as an additive to enhance properties, however, an excessive amount of the clay mineral showed degradation in strength of the mixtures.

During a study conducted to test if clay can act as an additive to mortar, where powdered clay was used, it was noticed that pure clay brick samples have a higher water absorption rate than samples that included 10% and 20% clay in the mortar mix. It was also evident that clay holds several positive results when added to a mortar mixture in terms of compressive strength. Compression strength test results of low water absorption also showed an impressive result when compared to samples having a high-water absorption. The clay present in the mortar mix acted as a filler as a more compact pore structure was formed (Stipalan et al. 2018). Abdul-Wahab et al. (2018) conducted a study to analyse the combined replacement of zeolite and kaolin in the production of concrete and their results show that 15% replacement of kaolin gave the best results in terms of compressive strength properties.

Conclusion

With the combination of additives with a slate debris mortar mixture in the hope of improving its properties, results might be similar to research carried out by these researchers. This is something that requires further exploration and the percentage dosage required of any admixture can be determined throughout trial mixes, therefore for this research, the same percentages of admixtures used in similar research will be considered to create a more durable sample of a slate debris mortar mixture.

Research Methodology

A quantitative approach was adopted in this paper since this approach uses quantifiable data to persuade facts and analyse patterns. This type of research approach involves using statistics and mathematical tools to acquire and interpret results.

Data was collected from mainly two different experimental procedures: one conducted by the researcher utilizing one’s property, while the other was conducted under laboratory conditions. The main experiment involved constructing five models, presenting a whole traditional roofing structure, one acting as a comparison model, meaning no additives were included, to resemble a traditional mixture like how it used to be done, while the other four were all constructed with different additives incorporated with the slate debris layer mix - two natural additives and another two man-made engineered additives. An amount of water was poured over these models mimicking rain and since the models were placed in an inclined position, water could slide off allowing for this water to be collected using containers. This experiment was repeated for different inclinations, each time observing certain features occurring at that moment and measuring the water being poured and the water being collected so one can estimate the amount of water the slate debris layer is absorbing and the time lag for water to percolate from each sample according to the
inclination set. The other experiment was conducted under laboratory conditions and consisted of a water absorption test on five samples of slate debris mixture.

**Quantity Mixtures**

Given the fact that minimal research was conducted regarding the addition of additives to a slate debris mortar mixture, the researcher included different quantity percentages adopted by other researchers’ results and recommendations on each additive when added to mortar or concrete in their study.

The pottery obtained for this study was a large earthenware pot. The pot was cleaned from any loose particles or debris and was then crushed using a hammer until small fragments of pottery were obtained. Hydrated lime used was obtained in powder form and was sieved for better results. To stimulate and try to mitigate a similar process of how lime was slaked in traditional times, the powdery lime was put in a container and was submerged underwater for a week before being used to form a slaked lime putty.

Using the 2:3 ratio of two parts lime and three parts crushed pottery adopted from Calleja et al. (2001), having known volumes required, weights required for each component were found by finding the density of each material. A cylinder with known volume was used, filled, and pressed cautiously with the material. It was then weighed so that the density of each component could be found, and the required weight could easily be found.

**Water Absorption Experiment**

Table 1 shows five different slate debris mortar mixtures. These were tested for their water absorption abilities in comparison with a traditional slate debris mortar mixture numbered as 1. The mixtures were all moulded in 100mm$^3$ wooden moulds and left to cure for seven days prior to starting experimentations. Slaked lime quantity was left consistent for each mixture as it was wise to do so since lime is the binder in these mixes. Tap water content was also left constant for each mixture. The only fluctuating component from the original mixture is the crushed pottery quantity as this was changed each time to accommodate the percentage replacement required for each additive. For mixture number 5, containing the cactus juice additive, water was not incorporated in the mixture. However, instead of water the same amount of cactus juice was used.

<table>
<thead>
<tr>
<th>Additive</th>
<th>%</th>
<th>Slaked Lime</th>
<th>Pottery</th>
<th>Tap Water</th>
<th>Fibre</th>
<th>Glass Powder</th>
<th>Kaolin</th>
<th>Cactus Juice</th>
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<td>3 Glass Powder</td>
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<td>4 Fibre</td>
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<td>5 Cactus Juice</td>
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**Table 1: Proportions used for each component to mould 100mm$^3$ samples**

The mixtures were moulded, labelled according to the number provided in Table 1 and left to dry for one week. Afterwards, each sample was then weighed on a measuring scale and
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documented in a tabulated format, prior to being submerged inside a water container. After an hour, the samples were removed from the water container, placed on a cloth, and slightly dried to remove any excess water, and were then re-weighed. The measured water absorption percentage of each sample was then determined.

Inclination and Absorption Experiment

The main experiment required the construction of a sectional model of a Maltese traditional roof. Fifty per cent proportions of each layer’s height were used to construct a miniature version of such structure. Perspex framing was used so one could observe clearly what happens to each layer of the section during experimentation.

![Diagram showing how the models were built up](image)

To form the *psisa* layer, stone pieces left from the stone cladding used beforehand were crushed using a hammer to form small random pieces of globigerina limestone fragments. These were then incorporated into the model. The screed layer, consisting of powdery fragments of globigerina limestone was again incorporated into the model and compressed to form a compact layer. For the last step before the slate debris layer, finer screed particles were incorporated to help form a levelled situation, and this was obtained using a small spirit level.

To construct each slate debris layer, the same approach to calculate component weights required as before was conducted. Table 2 represents the quantities used in the inclination experiment to construct the five-slate debris layers.

![Table 2: Components’ quantities used for each mixture](image)

Table 2: Components’ quantities used for each mixture
Once all the mixtures were prepared, each screed layer of the models was cautiously wetted so the slate debris layer could bond more profoundly with the layer underneath, and all the mixtures were spread evenly using a spatula and again levelled using a spirit level. These were then labelled according to the number given in Table 2 above and left to dry exposed to sunlight for a week.

For the data collection procedure, each model was assembled at an inclination, using a plastic wedge and a digital angle finder to help with the process. A known amount of water in grams was put inside a water sprout, so this could be used to interpret the idea of rain pouring on each model. The stopwatch was set to start and stop simultaneously while pouring water from the water sprout. Water slid off from the model with the help of the Perspex slide incorporated and was collected inside a container. The water collected was then re-weighed so one could calculate and analyse the amount of water that was lost through this process. Since human errors were easily an issue in this procedure, the same procedure for all five models was repeated three times so an average could be determined. Moreover, to minimise such errors, the researcher recorded this process each time so one could analyse certain minor observations that might not have been noticed during the procedure.

After conducting each experiment, the models were left exposed to exterior climate conditions for three days to be able to dry properly and the same procedure was repeated, each time using a different inclination.

Regression Analysis

To analyse data gathered from the inclination experiment, regression analysis was used to compare the different inclinations in relation to the different models. A hypothesis test was conducted using statistical software Minitab to statistically prove the significance of the results. Statistical significance quantifies if a result was due to a chance or due to a factor of interest. When a result is statistically proven, one would be more confident to document that the findings are real, rather than coincidental (Mcleod 2019).

All data collected was tabulated so that graphs and diagrams could easily be drawn up to help the researcher in the analysis of all the results gathered from the three experimental procedures. In this way, the additive with the highest ability to increase the slate debris’ properties could be documented.

Analysis of Research Findings

Water Absorption Test

After each slate debris sample was demoulded and subjected to a water absorption experiment, the dry weight and wet weight of each sample, following an hour submerged inside a water container, were recorded, and then tabulated.
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Water Absorption Test Results and Analysis

Figure 2: Bar chart showing percentage results obtained in water absorption testing

The lower the water absorption percentage was, the more effective the additive was in decreasing the penetration of water. Sample 1, being the traditional mix and acting as a comparative model, performed the worst in this experiment as it resulted in having the highest percentage absorption of 1.57%. The incorporation of the four additives used in this study all resulted in a drastic lower percentage value when compared to the value of sample 1. The sample with the lowest percentage of all, however, was the sample containing glass powder as an additive, which gave a percentage value of 0.63%. One needs to also consider the fact that sample 3 contained the highest percentage replacement of pottery fragments, as 20% of the pottery fragments ratio was replaced with glass powder. Each sample had different ratio percentages, as already explained, since minimal studies were conducted on this traditional slate debris mortar. Thus, percentage replacement decisions were based on other researchers’ findings when incorporating such additives into a concrete or mortar mixture. Considering that glass does not absorb water, this could be an indication of why such a result was achieved, but still a change of only 20% does not justify all this improvement. Thus, there could be something else which happened when this mix was chosen. One of the reasons could be the particle size of the glass powder which could have created better bondage than expected.

Inclination vs Water Penetration Regression Analysis

As can be seen in Figure 3, the results of different inclinations against how much water penetrated in each slate debris layer were plotted and the trendline of best fit was drawn up. Water lost was presented as a percentage per meter squared. At first glance, model 4, which consisted of polypropylene fibre additive, performed the best, while model 1, containing the traditional slate debris mixture, performed the worst. One can also observe that by the addition of any additive, there was always an improvement when comparing each model with model 1, even though some additives performed better than others.
Figure 3: Graph of Inclination vs Water Penetrated into Sample

Correlation can explain the relationship between a dependent and independent variable, while the $R^2$ value explains to what range the variance of a variable can explain the variance of another variable (Fernando 2020).

Since the points in Figure 3 follow a downward motion, this could imply that when one variable is increasing, the other variable is decreasing, and this relationship can be referred to as being an indirect relationship.

Considering the correlation values presented in Figure 3, each of the correlation values is quite accurate, however the most accurate value is 0.94 (model 3) while the least accurate value is 0.66 (model 5).
One can also observe the behaviour of each gradient and the y-intercept of the graph. In this experiment, the gradient indicated at what rate the water is running off from the slate debris layer and the x-intercept indicated how much water was absorbed by the layer if no inclination was present. Results show that the traditional mix has the highest run-off rate, but at the same time, it has the highest water penetration rate. Kaolin clay, polypropylene fibre and cactus juice mixtures have almost the same water run-off rate, although the polypropylene fibre mixture showed the best trend in not leaving water to be absorbed in the slate debris layer out of all the five.

Assuming the trendline will continue travelling at the same slope when it intersects the x-axis, one can identify the inclination of each model where water would most likely not penetrate through the model.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Equation of Trendline</th>
<th>Value of x when y=0 (degrees/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>y = -0.16x + 3.50</td>
<td>22.0°</td>
</tr>
<tr>
<td>2</td>
<td>y = -0.11x + 2.76</td>
<td>26.3°</td>
</tr>
<tr>
<td>3</td>
<td>y = -0.13x + 2.13</td>
<td>17.1°</td>
</tr>
<tr>
<td>4</td>
<td>y = -0.10x + 1.85</td>
<td>18.0°</td>
</tr>
<tr>
<td>5</td>
<td>y = -0.10x + 2.50</td>
<td>24.5°</td>
</tr>
</tbody>
</table>

Table 3: Values of x-intercept

Model 3 (glass powder additive) provides the lowest possible inclination, as, at an inclination of approximately 17°, the least amount of water to none would penetrate through the sample. The second best is model 4 (polypropylene fibre additive), where at an inclination of approximately 18° water would most likely not penetrate through the sample. However, one should consider that a small amount of water would most probably still penetrate through the slate debris layer or get lost through the process, even when one uses such inclinations that ensure water cannot penetrate as the absorption test showed. Therefore, if the graph were to be continually plotted accurately, it would most likely follow the path of an inversely proportional graph in the form of $y = \frac{k}{x}$, where $k$ is a constant rather than a straight-line graph since water would still penetrate through the model; however water lost would be at the minimum.
**Inclination vs Time**

The last test carried out was to collect the time taken for water to run off down the slope at different angles.

![Graph of Inclination vs Time Taken for Water to Run-Off from the Model's Upper Layer](image)

**Figure 4:** Graph of Inclination vs Time Taken for Water to Run-Off from the Model's Upper Layer

Considering Figure 4, since the points are following a downward motion, once again here is an indirect relationship between the two variables. Also, a positive correlation value is present since all the $R^2$ values are greater than 0. Each correlation value is quite accurate in such a case, as all the values are very close to 1. This indicates that the data collection was done almost accurately and that there exists a trend between the reading and inclination readings taken.

Results from this graph also show that model 4 (polypropylene fibre) performs the best while model 3 (glass powder) improves percolation at larger angles. Model 5 (cactus juice) resulted to be the worst in this experiment. This could indicate that the material created more friction for water to move on the said layer.

**Exploratory Analysis based on Regression Analysis**

For the following analysis, a statistical software, Minitab, was used to conduct a hypothesis test when comparing the regression coefficients. The traditional mix was compared to each
An Analysis of the Improvement of a Slate Debris (Deffun) Roof Properties with the Addition of Different Additives

mixture with an additive incorporated, in relation to water that has penetrated each sample and time taken for water to run off from the model’s upper slate debris layer. To conduct this analysis, the gradients of each line of best fit have been assumed to be identical.

Statistical Analysis based on Water Absorption

This hypothesis test was carried out to determine the difference between each model, between each inclination number to determine if the data is statistically proven. To conduct a hypothesis test on these different mixtures, when compared to the traditional mixture, one would need to assess the condition variable, which is the vertical difference between the two samples one is analysing. The p-value, if less than 0.05, shows that there is a statistical difference between the component when compared to the traditional mixture. Therefore, this evidence would allow for one to reject the null hypothesis, stating that the addition of additives to a slate debris (deffun) mixture has no effect on the water retention abilities, if there is a statistical difference between the two variables, and accept the alternative hypothesis stating that the addition of additives to a slate debris (deffun) mixture has a positive effect on the water retention abilities.

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
<th>SE Coefficient</th>
<th>T-Value</th>
<th>P-Value</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traditional vs kaolin clay</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
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<td>0.173</td>
<td>19.49</td>
<td>0.000</td>
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<tr>
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<td>0.0271</td>
<td>-4.88</td>
<td>0.002</td>
<td>1.00</td>
</tr>
<tr>
<td>Condition B</td>
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<td>0.162</td>
<td>-2.96</td>
<td>0.021</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Traditional vs glass powder</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
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<td>24.29</td>
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</tr>
<tr>
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<td>-6.45</td>
<td>0.000</td>
<td>1.00</td>
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<tr>
<td>Condition B</td>
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<td>-9.16</td>
<td>0.000</td>
<td>1.00</td>
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<tr>
<td><strong>Traditional vs polypropylene fibre</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>0.175</td>
<td>19.27</td>
<td>0.000</td>
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<td>1.00</td>
</tr>
<tr>
<td><strong>Traditional vs cactus juice</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.003</td>
<td>1.00</td>
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<td>-4.10</td>
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<td>1.00</td>
</tr>
</tbody>
</table>

Table 4: Statistical analysis based on the differences between Regression lines related to water absorption

Table 4 above indicates that the highlighted p-value is always less than 0.05 which indicates that all mixes resulted to perform better than the traditional one and this was statistically proven. Also, the term highlighted under the coefficient column indicates the
vertical difference between the traditional mix and all other mixes. The mix including the polypropylene fibre had the highest displacement, thus indicating the best mix out of the five samples. The mix that contained glass fibre did perform well with a slight lower difference from the polypropylene fibre mix. This mix offers a second option for improving the slate debris layer and considering the test carried out to find out the water absorptivity, the glass powder mix did offer the best results. Covering research based on the compression strength of both mixes will give a better indication of which mix would be ideal to use to create a slate debris layer on roofing structures.

Statistical Analysis Based on the Time Taken for Water to Run Off

Another hypothesis test was carried out on all four additive mixtures which were compared with the traditional mixture with the time taken for water to run off the model.

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
<th>SE Coefficient</th>
<th>T-Value</th>
<th>P-Value</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional vs kaolin clay</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
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<td>Condition B</td>
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<td>0.20</td>
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<td>Constant</td>
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<td>Traditional vs polypropylene fibre</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>38.45</td>
<td>1.99</td>
<td>19.28</td>
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<td>-0.39</td>
<td>0.706</td>
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</tr>
<tr>
<td>Traditional vs cactus juice</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1.54</td>
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<td>1.00</td>
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<td>Condition B</td>
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<td>1.44</td>
<td>2.04</td>
<td>0.081</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 5: Statistical analysis based on the differences between Regression lines related to time taken for water to run off

This time results showed that there is no statistical difference between the traditional mix and all four other mixes. This result indicates that changing or introducing another compound with the mix does not improve the water run-off from the roof structure. Still, one should note that slate debris layers have a rough surface. Introducing these four
different compounds does not improve the roughness of the surface. To smoothen out this surface, one needs to redesign the mix and includes smaller particles to better level the floor.

Conclusion

This research focused on the possibility of improving the parameters of slate debris for roofing purposes. Results have shown that by using any one of the four mixes researched, the slate debris will improve mostly the water absorption properties.

The additive that has ranked the highest of all was polypropylene fibre. As already mentioned, during restoration works that were carried out on a local chapel, the conservation architect incorporated polypropylene fibre to the new slate debris mortar mixture with the mindset of increasing the shear capacity and prevention of mortar shrinkage of the new mixture (Chetcuti 2006). Comparing results obtained from this study to this incorporation of polypropylene fibre in restoration works, the architect was right to do so. This study confirmed the improvement in the properties of the slate debris layer when mixed with polypropylene fibre. Presently, the slate debris roofing system requires excessive maintenance and only a limited number of services can be incorporated on such roof. With the incorporation of this additive, a slate debris roofing system might have the ability to withstand more forces acting upon it, such as the addition of services to be left on the roof. Research carried out to check different proportions of polypropylene fibre with the rest of the mix would further indicate if the properties improved or not.

The glass powder also gives another option, ranking second. During the experiments conducted, this additive has managed to also increase the mixture’s abilities. 20% of glass powder to pottery aggregate replacement was used in this study, and when comparing these results to other research conducted on this material 20% was the right amount of percentage replacement to create concrete finishes. According to Soliman et al. (2016), the highest percentage of glass powder should not exceed 20% to have a high-performance mixture, and Islam et al. (2016) confirmed this as when this percentage was increased, there was a decrease in water retention abilities. Still, 20% mix with slate debris might not be the best mix and for such more studies should be carried out if one wants to adopt this type of mix.

As indicated by the results found in Table 3, it is always better to increase the inclination of the roof structure to reduce the chance of water penetration and absorption. Incorporating polypropylene fibre with the traditional mix would enable an inclination of approximately 18° to be ideal. It is always possible to reduce the inclination, but then the amount of water absorbed could increase, in which case it would not be feasible.
References


