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Modular system design for vegetated surfaces with alkaline activated materials

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To Artur and Rui who brought more joy into my life.

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Resumo

O sector da construção e o sector das indústrias extrativas são os maiores produtores de resíduos, representando cerca de 35% e 28%, respetivamente, do total de resíduos produzidos na União Europeia. Atendendo a este facto torna-se fundamental desenvolver soluções construtivas inovadoras com base no reaproveitamento destes resíduos criando novos materiais com valor acrescentado.

Este trabalho apresenta a conceção de um sistema modular para execução de superfícies ajardinadas com materiais de ativação alcalina (Geogreen). O sistema modular para superfícies ajardinadas destaca-se na área de materiais de construção, diferenciando-se dos demais sistemas de coberturas e fachadas ajardinadas existentes pelas suas características construtivas, pelos materiais incorporados e pela integração de princípios de sustentabilidade.

Os resultados demonstram que este sistema modular contribui não só com a função estética de um revestimento ajardinado mas também permite melhorar as condições térmicas e acústicas da envolvente edificada, contribuindo para o mercado da construção com uma solução mais sustentável, pela integração de resíduos e soluções de minimização de energia incorporada.

Palavras-chave

Sistema modular, superfícies ajardinadas, coberturas ajardinadas, fachadas ajardinadas, materiais de ativação alcalina, análise térmica, acústica de edifícios, análise de ciclo de vida.

Resumo alargado

Enquadramento

Este trabalho apresenta a conceção de um sistema de peças modulares para execução de superfícies ajardinadas incorporando materiais de ativação alcalina. Os primeiros estudos sobre este sistema modular resultaram do projeto de investigação PTDC/ECM/113922/2009 com a designação "GEOGREEN, Waste geopolymeric binder-based natural vegetated panels for energy-efficient building green roofs and facades", desenvolvido no C-MADE, Centre of Materials and Building Technologies, entre 2011 e 2014, os quais deram lugar a uma primeira patente de invenção nacional PT106022. O presente trabalho surge na sequência desse trabalho de investigação e integra-se no âmbito da Bolsa de Doutoramento SFRH/BD/98422/2013, financiada pela Fundação para a Ciência e Tecnologia sob o programa QREN - POPH/FSE, co-financiada pelo Fundo Social Europeu e por fundos nacionais do Ministério da Educação e da Ciência.

Descrição do problema

Com o crescimento das áreas urbanas e a sua densificação de forma insustentável, tem vindo a verificar-se uma deterioração das suas condições ambientais. A concentração de materiais que absorvem quantidades elevadas de radiação solar dá origem a um sobreaquecimento das áreas urbanas, especialmente no período noturno, fenómeno designado por "efeito de estufa" [1]. O aumento da impermeabilização dos solos e a falta de espaços permeáveis, levam também a que, as águas pluviais não sejam drenadas naturalmente, aumentando a escorrência superficial e consequentemente os caudais de drenagem de águas pluviais. Outro problema que deriva do crescimento dos espaços urbanos consiste no incremento do uso do automóvel em áreas urbanas, o que se repercute no aumento dos níveis de poluição e consequente deterioração da qualidade do ar.

A integração de vegetação pode ser um importante contributo para minimizar estes problemas, beneficiando quer o contexto urbano quer o próprio edificado. O uso de vegetação na envolvente edificada apresenta diversos benefícios ambientais, sociais e económicos, daí que, tenha surgido uma crescente investigação sobre esta temática. Além disso, o relatório final Horizonte 2020 refere o uso de soluções baseadas na natureza, como uma estratégia para criar sociedades mais sustentáveis e resilientes [2].

A Diretiva relativa ao desempenho energético dos edifícios da União Europeia [3] menciona também que, até 2020, todos os edifícios novos devem ser "energia zero". O objetivo desta iniciativa é promover o desempenho energético de edifícios novos e reabilitação de grandes edifícios existentes, minimizando sua dependência energética e as emissões de gases de efeito estufa. Assim sendo, é importante aumentar o uso de sistemas eficientes de aquecimento e arrefecimento, utilizando fontes de energia renováveis e soluções de design passivo, como fachadas ajardinadas ou coberturas ajardinadas.

É importante também salientar que o sector da construção e o sector das indústrias extrativas são os maiores produtores de resíduos, representado cerca de 35% e 28%, respetivamente, do total de resíduos produzidos na União Europeia [4]. Atendendo a este facto torna-se fundamental desenvolver soluções construtivas inovadoras com base no reaproveitamento destes resíduos criando novos materiais com valor acrescentado.

Este trabalho tem como objetivo demonstrar como resíduos industriais e outros materiais reciclados podem fazer parte do novo sistema para superfícies ajardinadas e como as características do próprio sistema podem contribuir como uma estratégia sustentável para melhorar o conforto dos edifícios.

Argumento de tese

Esta tese propõe uma nova abordagem no âmbito dos sistemas de coberturas e fachadas ajardinadas no que se refere à conceção de um sistema modular inovador quanto ao tipo de materiais utilizados e características construtivas.

A conceção deste sistema visa integrar princípios de sustentabilidade. Para tal são integradas soluções de minimização de consumo de recursos naturais, favorecendo a utilização de resíduos e materiais reciclados na sua composição e promovendo a redução das necessidades de irrigação, através da absorção e retenção de água e uso de plantas adaptadas ao clima local. Por outro lado recorre-se à avaliação do seu impacte ambiental e propõem-se soluções de minimização de consumo de energia incorporada no processo produtivo.

Este sistema visa também aumentar o conforto dos espaços interiores contribuindo para a melhoria das características térmicas e acústicas da envolvente edificada.

Principais objetivos

Assim sendo, este trabalho tem como metodologia:

- Pesquisar soluções tradicionais e novas conceções de sistemas de coberturas e fachadas ajardinadas existentes e sistematizar as suas características e benefícios;
- Identificar soluções de integração dos sistemas ajardinados no contexto urbano;
- Projetar um sistema de peças modulares para a execução de superfícies ajardinadas promovendo a utilização de materiais não convencionais de ativação alcalina obtidos a partir de resíduos e de outros materiais naturais e sustentáveis;
- Estudar a composição de cada camada constituinte do sistema construtivo proposto;
- Sistematizar e pormenorizar construtivamente o sistema tendo em conta as diferentes condicionantes do seu posicionamento horizontal ou vertical, permitindo a sua instalação em edifícios novos ou na reabilitação de edifícios existentes;
- Efetuar o cálculo do número e tipo de apoios de suporte das peças modulares visando identificar qual o melhor sistema de apoio para as peças modulares;
- Efetuar uma análise de custos do sistema, estabelecendo uma comparação com outros sistemas convencionais para o mesmo fim;
- Realizar testes laboratoriais para avaliar as características físicas (nomeadamente resistência à compressão, absorção de água por capilaridade e densidade) de diversas misturas de materiais de ativação alcalina de modo a identificar a composição que mais se adequa ao sistema modular;
- Testar parâmetros indicadores de desempenho térmico do sistema modular quando aplicado como fachada ajardinada, através da realização de medições *in situ*, num local com condições climáticas reais;
- Testar parâmetros indicadores de desempenho acústico do sistema modular;
- Efetuar uma análise de ciclo de vida do sistema modular com vista à avaliação da sustentabilidade do sistema no que se refere à escolha dos materiais e processo produtivo;
- Analisar os resultados obtidos, estabelecer recomendações de melhoria e apresentar possíveis desenvolvimentos futuros.

Metodologia

Em primeiro lugar, desenvolveu-se uma pesquisa de soluções atuais e inovadoras de coberturas e fachadas ajardinadas, sendo que algumas ainda não estão no mercado e apenas possuem publicação das suas patentes. Seguiu-se a análise de como esses sistemas podem contribuir para melhorar o espaço urbano.

Com base no conhecimento adquirido relativamente às soluções existentes de coberturas e fachadas ajardinadas, foi desenvolvida uma solução inovadora para o sistema modular proposto para superfícies ajardinadas. O estudo de conceção deste sistema foi seguido pelo desenvolvimento de vários estudos científicos relacionados com as propriedades deste sistema para criação de superfícies ajardinadas que resultaram na publicação de alguns artigos científicos. Neste contexto, foram testadas as propriedades de materiais de ativação alcalina visando melhorar sua adequação ao sistema modular proposto. Além disso, foram avaliados alguns benefícios térmicos e acústicos deste sistema. Finalmente apresenta-se um estudo comparativo sobre a análise do ciclo de vida do novo sistema modular.

Principais contribuições

Revisão bibliográfica de coberturas e fachadas ajardinadas

Este trabalho visa, num contexto geral, complementar o conhecimento no âmbito das soluções de revestimentos ajardinados, nomeadamente coberturas e fachadas ajardinadas. Para tal é apresentada uma sistematização dos diversos sistemas e uma análise das suas características construtivas. Este trabalho inclui também uma revisão bibliográfica dos benefícios associados aos sistemas de revestimento ajardinados, quer para o contexto urbano quer para a envolvente edificada.

Conceção de um sistema modular de superfícies ajardinadas

Este trabalho apresenta a conceção de um sistema de peças modulares para superfícies ajardinadas para aplicação em edifícios novos e edifícios existentes. Este sistema visa ser de simples montagem e desmontagem, permitindo criar superfícies ajardinadas de forma rápida e eficaz, ser adaptável a diferentes superfícies e inclinações e possibilitar a sua aplicação na construção ou reabilitação de coberturas, fachadas e outros elementos edificados.

Este trabalho explora novas possibilidades de conceção de peças modulares para coberturas e fachadas ajardinadas recorrendo a novas formas e geometrias mediante moldagem, corte e fresagem com CNC. As peças modulares podem adquirir diferentes configurações e inclinações conforme as necessidades de aplicação e enquadramento arquitetónico.

Este estudo deu origem a uma configuração específica de peças modulares a qual mereceu um estudo mais aprofundado das suas características construtivas, do seu método de fixação e dos materiais a integrar. Cada módulo deste sistema é composto por uma base executada com um material de ativação alcalina, resistente e porosa e por um elemento superior leve em aglomerado negro de cortiça expandida com aberturas onde são introduzidas diversas espécies de plantas endémicas. O sistema de fixação das peças modulares é calculado com o objetivo de proporcionar a sua aplicação quer em coberturas quer em fachadas e de minimizar o número de apoios por peça.

Aplicação de materiais de ativação alcalina num revestimento ajardinado

Os estudos apresentados demonstram uma evolução no conhecimento de materiais de ativação alcalina e de integração dos mesmos em novas aplicações arquitetónicas. Nomeadamente, quanto à sua utilização num sistema modular de coberturas e fachadas ajardinadas.

Este sistema distingue-se dos demais sistemas modulares por integrar na sua composição as potencialidades de materiais de ativação alcalina, partindo da reutilização de resíduos industriais. Os testes de novas composições de materiais de ativação alcalina (geopolímeros) baseiam-se em misturas com base no reaproveitamento de resíduos industriais (lamas das minas da Panasqueira e vidro reciclado) e na adição de diversos agregados. Este estudo suporta-se no equipamento e conhecimento disponível na unidade de investigação e desenvolvimento C-MADE, *Centre of Materials and Building Technologies,* sobre materiais de ativação alcalina realizados com resíduos de minas.

Estudos recentes demonstram que as lamas residuais das minas da Panasqueira possuem uma composição rica em alumino-silicato, sendo consideradas um material muito promissor para a produção de materiais de ativação alcalina, tanto do ponto de vista ambiental como económico. Os materiais de ativação alcalina (ligantes geopoliméricos) obtidos até à data apresentam elevada resistência à compressão e boa resistência à abrasão e aos ácidos. Importa salientar que a lixiviação de metais pesados dos materiais de ativação alcalina obtidos a partir de lamas residuais das minas da Panasqueira é muito reduzida, revelando-se a ativação alcalina como um processo muito seguro de encapsulamento destes metais pesados [5, 6]. O presente estudo tem em conta esta análise e considera-a uma premissa fundamental para a validação do sistema proposto.

A mistura base de ativação alcalina foi sujeita a diversas combinações visando a obtenção de uma mistura com a melhor resistência à compressão. Neste contexto foram testadas diversas percentagens de cada precursor (lama e vidro), diferentes temperaturas de cura e de concentração molar de hidróxido de sódio. Após a definição da mistura base foram adicionados diferentes tipos de agregados (areia, regranulado negro de cortiça e argila expandida) à mistura com o propósito maximizar a capacidade de absorção de água por capilaridade e minimizar a densidade da mistura, garantindo uma adequada resistência à compressão para esta função.

Melhoria das condições de conforto térmico e acústico dos edifícios

Neste trabalho procedeu-se à realização de testes com protótipos à escala real para avaliar como este sistema modular para execução de revestimentos ajardinados pode contribuir para melhorar o desempenho térmico e acústico da envolvente edificada.

A análise térmica foi realizada ao longo de diversos períodos numa câmara de teste exterior com condições climáticas reais. Este estudo estabeleceu uma avaliação comparativa da temperatura superficial e do fluxo de calor de uma parede de referência e de uma parede com características idênticas revestida com o sistema modular desenvolvido.

A avaliação acústica do sistema modular consistiu na identificação de como alguns fatores como os materiais, o substrato, as plantas e a sua variedade e altura interferem com as condições de absorção sonora deste sistema ajardinado.

Estratégias de minimização de impacte ambiental

Este trabalho foca-se também na integração de medidas de sustentabilidade no desenvolvimento deste sistema modular. A aplicação de materiais de ativação alcalina obtidos visa promover a reciclagem e valorização de resíduos, contribuindo para a minimização do consumo de recursos naturais. As características estudadas nestes materiais visam permitir que estes absorvam água e a transmitam lentamente para as plantas. O uso de vegetação adaptada ao clima local visa simultaneamente minimizar as necessidades de irrigação, enquanto contribui para a retenção de dióxido de carbono.

A aplicação de aglomerado negro de cortiça no sistema modular resulta do facto de este ser um material sustentável e com um reduzido impacte ambiental. Para além disso este material possui propriedades térmicas e acústicas que podem contribuir para melhorar as características da envolvente edificada.

Neste âmbito foi também desenvolvida uma análise comparativa do ciclo de vida (ACV) com o objetivo de avaliar os benefícios ambientais a longo prazo deste sistema. Este estudo integrou a comparação de diversos fatores de impacte ambiental, o que permitiu identificar quais os processos com maior consumo energético e consequentemente levou a uma avaliação de estratégias de minimização de energia incorporada e de emissões de CO_2 do sistema. Este sistema modular foi também comparado com outros sistemas ajardinados e de revestimento para se estabelecer uma análise comparativa em diferentes categorias.

Estado da Arte

Contexto histórico

Os elementos vegetais desde sempre marcaram a sua presença no edificado. É de salientar exemplos emblemáticos como os Jardins Suspensos da Babilónia, baseados em construções em terraço repletos de vegetação em seu redor. Outros exemplos notáveis reportam aos Impérios Grego e Romano onde as videiras, castanheiros e oliveiras [7] eram usados para sombrear o edificado. Nos países escandinavos, como a Islândia e a Noruega, as coberturas ajardinadas com turfa fazem parte da arquitetura vernacular [8], sendo que algumas destas construções permanecem preservadas até aos dias de hoje.

Os jardins instalados em coberturas são uma prática antiga, contudo foi na Alemanha, durante as décadas de 1960 a 1980, que se intensificou a investigação em torno das coberturas ajardinadas extensivas, tendo sido largamente utilizadas para controlo de chuva em áreas densamente povoadas [9]. Nas décadas subsequentes, algumas iniciativas governamentais alemãs incentivaram a aplicação de coberturas ajardinadas, tendo alcançado cerca de um milhão de metros quadrados de coberturas ajardinadas em 1989, e chegando a atingir os dez milhões de metros quadrados de coberturas ajardinadas em 1996 [10]. Alguns destes exemplos permanecem ainda hoje em boas condições, o que serve de indicador da durabilidade das soluções implementadas. No início do século XX as coberturas ajardinadas fizeram parte da vanguarda arquitetónica estando integradas em projetos de Le Corbusier, Walter Gropius e Frank Lloyd Wright [7].

Nos séculos XVII e XVIII vulgarizou-se a utilização de trepadeiras nas fachadas de edifícios Europeus [11] e mais tarde no século XIX esta solução expandiu-se para os Estados Unidos da América. Na década de 1980 o uso de trepadeiras intensificou-se, maioritariamente, na Alemanha, onde foram criados programas de incentivo à instalação de fachadas verdes. Segundo Manfred Köhler, estima-se que em Berlim, entre 1983 e 1997, tenham sido instalados cerca de 245 584m^2 de fachadas ajardinadas [9].

Incentivos à instalação de sistemas ajardinados

Constitui um desafio emergente, expandir, qualificar e diversificar a estrutura verde urbana, de modo a fixar os residentes e a tornar a cidade mais sustentável (em termos ambientais, económicos e socioculturais) [12]. As entidades políticas de diversas cidades Norte-americanas como Chicago, Portland, Filadélfia ou Toronto reconhecem as vantagens e os benefícios da inserção de revestimentos ajardinados em edifícios novos e existentes, tendo criado incentivos à instalação de coberturas ajardinadas, de modo a promover a sustentabilidade urbana [13]. Medidas semelhantes têm vindo a difundir-se pela Europa, como em Copenhaga [14] ou Londres [15]. Pelo Oriente, importa salientar o caso de Singapura que, apesar da elevada densidade urbana, já integra 100ha de revestimentos ajardinados, entre coberturas e fachadas ajardinadas e visa duplicar esta área até 2030 através do Programa Skyrise Greenery Incentive Scheme. Neste caso são apresentadas também algumas estratégias de informação dos intervenientes acerca da correta instalação dos sistemas ajardinados e da sua correta manutenção. Sendo que estas são também medidas fundamentais à proliferação da aplicabilidade de revestimentos ajardinados em edifícios.

Presentemente, o mercado está a adaptar-se a novas solicitações, procurando-se soluções de coberturas e fachadas ajardinadas inovadoras e eficientes. Os sistemas de coberturas ajardinadas têm vindo a ser largamente disseminados. Contudo, o fomento à aplicação de paredes vivas (Living walls) está ainda em crescimento.

Sistemas ajardinados e suas características

Para melhor identificar e sistematizar os sistemas de coberturas e fachadas ajardinadas importa analisar a sua composição por camadas, a função de cada elemento que os compõem e classificar os sistemas construtivos consoante as suas principais características técnicas.

Coberturas ajardinadas

As coberturas ajardinadas são habitualmente classificadas em função das suas camadas. Neste âmbito destacam-se as coberturas extensivas e as coberturas intensivas.

As coberturas extensivas são sistemas leves, de espessura reduzida, que podem ser instalados em coberturas existentes não transitáveis, planas ou com inclinação até 30º, sem constituírem uma sobrecarga para a estrutura [10]. Embora a espessura do sistema limite o tipo de plantas a instalar, estes sistemas podem cobrir áreas extensas, devendo optar-se por plantas adaptadas às condições climáticas locais. As coberturas extensivas são soluções sem grandes dificuldades técnicas de instalação, necessitando apenas de irrigação e manutenção ocasionais.

As coberturas intensivas são habitualmente aplicadas em coberturas transitáveis com capacidade de carga e profundidade suficiente para instalar uma camada de substrato que permita o desenvolvimento de gramíneas, arbustos e árvores de pequeno e médio porte. Ao conterem uma camada de substrato de maior espessura, contribuem para o isolamento térmico e acústico da própria cobertura. Porém, estes sistemas possuem necessidades de irrigação e manutenção regulares [10].

Alguns autores referem a existência de uma terceira classificação, as coberturas ajardinadas semi-intensivas [16]. Estes sistemas possuem características intermédias, visando incorporar características dos sistemas extensivos e intensivos [7]. Estes sistemas contêm uma espessura intermédia, possibilitando a integração um maior número de espécies de plantas do que as coberturas extensivas e minimizando as necessidades de manutenção e irrigação quando comparadas com as soluções intensivas.

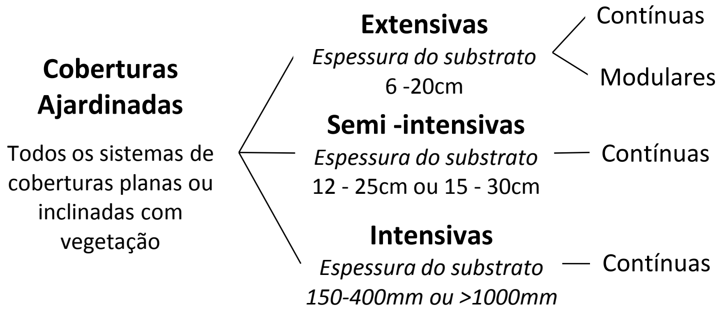

Figura 1 - Sistemas de coberturas ajardinadas [17]

No contexto das coberturas extensivas têm surgido soluções alternativas, como os sistemas modulares e os sistemas contínuos pré-enraizados. Estes possuem vantagens de instalação, que permitem criar superfícies ajardinadas num curto espaço de tempo. A leveza destas soluções, e a possibilidade de substituição de peças modulares tornam também a manutenção e reparação mais expeditas.

Algumas soluções, quer modulares quer contínuas, preveem não só a instalação em coberturas planas, mas também em coberturas inclinadas. Nestes casos deve existir um elemento que sustente o sistema ajardinado e que favoreça o enraizamento das plantas, evitando que o substrato deslize.

Os sistemas de coberturas ajardinadas contínuas são habitualmente compostas por um conjunto de camadas de proteção e de melhoria da performance do sistema. Avaliando-as no sentido ascendente destacam-se os seguintes elementos: camada de impermeabilização, tela anti-raízes, membrana ou camada drenante, tela filtrante, meio de crescimento e vegetação. Estes elementos poderão assentar sobre uma estrutura existente ou projetada para o efeito, devendo existir uma camada de forma com uma pendente mínima de 1.5 a 3% proporcionando uma adequada drenagem da cobertura. Para tornar as coberturas mais leves, flexíveis e garantir baixos custos, é frequente recorrer-se a materiais poliméricos, os quais podem ser transportados para a cobertura manualmente, em rolos, sendo de fácil aplicação [18].

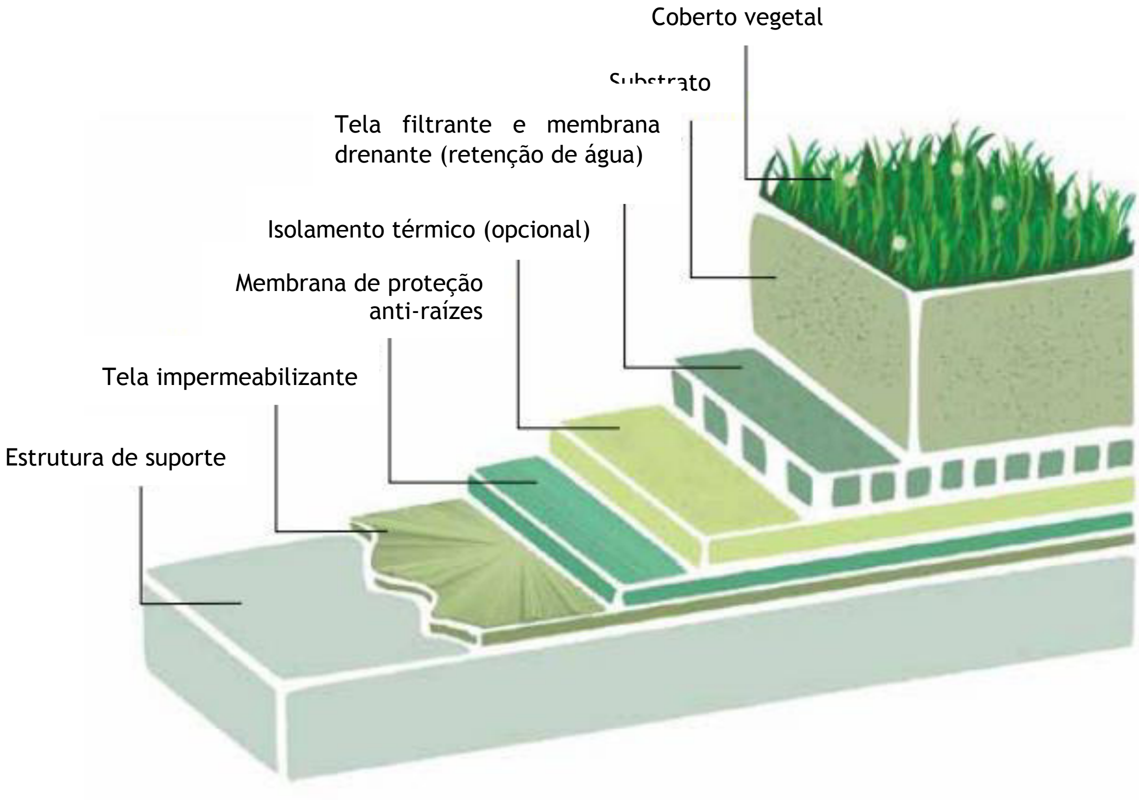

Figura 2 – Composição de uma cobertura ajardinada extensiva [19].

Isolamento térmico

Dependendo do tipo de sistema e da espessura da camada de substrato, pode ser necessário aplicar-se uma camada de isolamento térmico. Existem alguns sistemas em que esta camada se situa sob a camada de impermeabilização e outros, designados "sistemas invertidos", em que o isolamento é instalado sobre a impermeabilização [20].

Impermeabilização

A estrutura onde assenta a cobertura ajardinada deve estar devidamente impermeabilizada a fim de evitar infiltrações. O sistema de impermeabilização deve garantir a dilação e contração da estrutura sem que este fissure, impedindo assim a penetração de água. Para evitar a sua deterioração este sistema pode conter aditivos químicos anti-raízes.

Drenagem

No caso das coberturas ajardinadas extensivas é frequente aplicar-se uma membrana drenante leve, em material polimérico, com uma matriz tridimensional de reentrâncias semicónicas (de dimensão definida pelo fabricante) que recebe o excesso de água contida no substrato e acumula-a em pequenos depósitos, evitando o encharcamento do substrato e o apodrecimento das raízes. No caso de ser em excesso encaminha-a para o sistema de drenagem de águas pluviais. Algumas soluções incluem dois geotêxteis nas faces, superior e inferior, da manta drenante. O feltro laminado da face inferior destina-se à proteção do sistema de impermeabilização e o feltro superior funciona como tela filtrante e anti-raízes. No caso de coberturas ajardinadas intensivas, a camada de drenagem pode possuir uma capacidade de carga muito superior, sendo frequente utilizarem-se agregados cuja densidade pode ultrapassar os $8kg/m^2$ por cada centímetro de profundidade [21].

Tela anti-raízes

A tela anti-raízes tem como objetivo evitar a proliferação das raízes para a estrutura, evitando o aparecimento de fissuras e a passagem de água para as superfícies inferiores. No mercado existem dois tipos de sistemas, os químicos e os físicos [18]. Os sistemas físicos são habitualmente telas poliméricas que podem ser aplicadas sobre a estrutura do edifício. Os sistemas químicos baseiam-se na utilização de toxinas, como o cobre, embebidas na própria tela impermeabilizante, que evitam a proliferação de raízes.

Tela filtrante

A tela filtrante é usualmente aplicada abaixo da camada de substrato a fim de evitar a migração de partículas que possam eventualmente bloquear a drenagem da cobertura. Usualmente são utilizadas telas de peso e espessura reduzidas, as quais podem vir fixas diretamente à superfície superior da tela drenante, facilitando a sua aplicação [18]. Para este fim é frequente aplicarem-se telas porosas mas resistente ao punçuamento, formadas por um tecido não tecido de fibras sintéticas.

Retenção de água

Complementarmente pode aplicar-se uma camada de retenção de água que absorva a água da chuva ou do sistema de irrigação e a liberte lentamente para o substrato. A necessidade de retenção de água pode ser muito variável, pois depende das condições climáticas locais, do tipo de sistema – extensivo ou intensivo, das necessidades da vegetação e das características do meio de crescimento.

Meio de Crescimento

O meio de crescimento fornece os nutrientes necessários ao desenvolvimento das plantas e um meio de proliferação das suas raízes. Este pode ser composto por elementos inorgânicos, elementos orgânicos ou pela combinação de ambos. Podem efetuar-se diversas composições de substrato, existindo desde misturas industriais analisadas para fins específicos, a misturas personalizadas em função do tipo de sistema e de plantas a instalar. A mistura do meio de crescimento deve estabelecer um equilíbrio entre a sua espessura, o seu peso e as necessidades das plantas.

Vegetação

A aplicação de vegetação em coberturas ajardinadas é fortemente condicionada pelas características físicas da cobertura, nomeadamente no que se refere a espessura da camada de substrato e da capacidade de carga da cobertura. No caso das coberturas ajardinadas extensivas, diversos estudos indicam o uso de plantas suculentas (e.g. *Sedum*). Este tipo de vegetação possui elevada resistência a condições climáticas extremas e um peso reduzido, aproximadamente 10 Kg/m^2.

No caso de coberturas intensivas pode aplicar-se uma maior variedade de espécies. Para superfícies com espessuras acima de 15cm ou 20cm, podem aplicar-se gramíneas e arbustos, cujo peso ronda os 10 Kg/m^2. Em superfícies com espessuras superiores a 0.90m é possível aplicar-se todas as espécies referidas anteriormente e inclusivamente arbustos com cerca de 20 Kg/m^2 ou mesmo árvores de pequeno porte [21].

De facto as condições ambientais ao nível do edifício são distintas das condições no solo, pelo que as superfícies ajardinadas podem integrar um número restrito de espécies [1], atendendo ao contexto em que se inserem. As coberturas estão expostas a condições climáticas extremas (e.g. exposição solar permanente, falta de irrigação, ventos fortes, entre outras) e possuem uma camada limitada de substrato para o desenvolvimento de raízes com uma quantidade finita de nutrientes, o que pode determinar as suas necessidades de irrigação.

A vegetação deve adequar-se, quer ao tipo de sistema, quer ao clima local. As plantas mais adequadas para instalar nas coberturas e fachadas ajardinadas são as espécies autóctones ou nativas, que estão adaptadas ao clima local e possuem menores necessidades de irrigação.

Irrigação

As necessidades de irrigação dependem das condições do clima local, do próprio sistema e do tipo de plantas a instalar. No caso das coberturas intensivas, a irrigação pode ser fundamental para o desenvolvimento da vegetação, atendendo a que estas podem integrar elementos de maior porte e com maior desenvolvimento das suas raízes. No caso das coberturas extensivas pode evitar-se a implementação deste sistema, desde que se utilizem plantas habituadas a sobreviver em condições de seca. Uma alternativa interessante consiste na recuperação das águas pluviais ou mesmo a reciclagem de águas pretas e cinzentas do edifício [22] e o aproveitamento das mesmas para irrigar as superfícies ajardinadas em edifícios.

Fachadas ajardinadas

Presentemente verifica-se um acentuado desenvolvimento de novos sistemas de fachadas ajardinadas. Entre os diversos sistemas existentes podem destacar-se duas tipologias [18] [23], as tradicionais fachadas verdes (green façades) e os novos sistemas de paredes vivas (living walls).

As soluções de fachadas verdes tradicionais consistem na utilização de trepadeiras (perenes ou caducas), enraizadas no pavimento ou inseridas em vasos, que se desenvolvem no sentido ascendente ao longo da superfície a revestir. As soluções contemporâneas de fachadas verdes possuem um sistema de guias fixo à parede para direcionar o desenvolvimento da vegetação. As fachadas verdes são soluções económicas e de simples execução, apresentando, contudo, um crescimento disperso e demorando algum tempo a criar uma superfície contínua de vegetação.

Quanto às *paredes vivas*, estas incluem os sistemas modulares e os jardins verticais. As *paredes vivas* vieram permitir um rápido revestimento vegetal de superfícies de grandes proporções, adaptando-se a vários tipos de edifícios e a diversas condicionantes. Estas soluções garantem um crescimento da vegetação mais uniforme ao longo de toda a superfície e permitem a utilização de uma maior variedade de espécies de plantas, podendo desenvolver-se soluções artísticas, explorando-se as tonalidades, densidade da folhagem e padrões da vegetação.

Os *sistemas modulares* consistem na aplicação de módulos, com dimensão e composição variáveis, contendo o meio de crescimento e a vegetação, que podem ser conectados entre si e fixos à superfície vertical.

Figura 3 – Da esquerda para a direita: Quinta das Lapas, Torres Vedras [24]; Sistema Modular, Sede da MSF, Lisboa [25]; Jardim Vertical de Patrick Blanc, Caixa Forum, Madrid (Junho,2011).

Os *jardins verticais* consistem na aplicação de materiais leves como telas geotêxteis, onde são introduzidas individualmente as plantas [8]. A solução mais conhecida nesta área reporta ao trabalho do botânico Patrick Blanc, cujo sistema surgiu pela primeira vez em 1994 [26]. Neste momento Patrick Blanc já instalou jardins verticais por todo o mundo, tendo integrado o seu trabalho em diversas obras arquitetónicas de arquitetos famosos. Trata-se de um sistema hidropónico, leve e sem substrato, que pode ser instalado quer em fachadas novas, quer na recuperação de edifícios existentes [26].

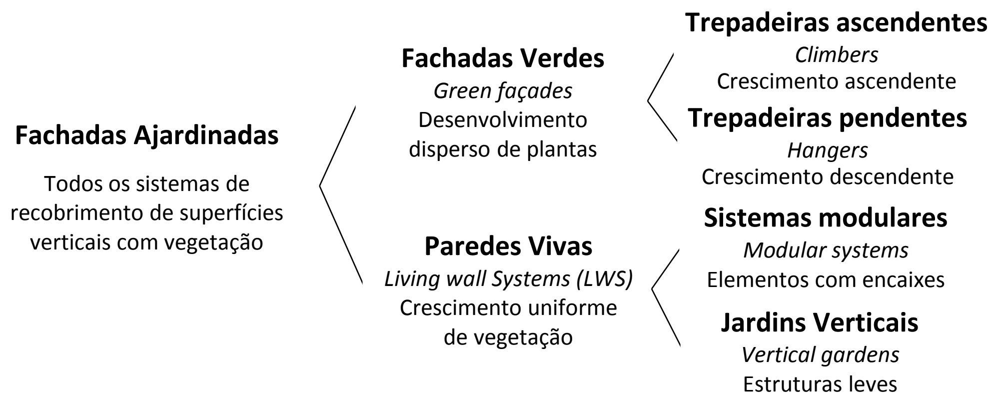

Figura 4 - Sistemas de fachadas ajardinadas

A composição dos sistemas de fachadas ajardinadas é muito variável, dependendo do sistema a implementar. Contudo, podem salientar-se os seguintes elementos: estrutura de suporte, drenagem, meio de crescimento, vegetação e irrigação.

Estrutura de suporte

Nas soluções de fachadas verdes tradicionais as plantas trepadeiras protegem a envolvente edificada dos agentes externos. Contudo, as suas raízes podem degradar a superfície, podendo atrair alguns animais indesejados e obrigar a um trabalho de manutenção constante, para guiar o seu desenvolvimento. Atualmente, existem diversos materiais que permitem suportar e guiar o desenvolvimento de trepadeiras, possibilitando o afastamento da vegetação das fachadas e criando uma camada de ar entre a parede e a vegetação, funcionando como uma fachada ventilada.

No caso dos sistemas modulares, estes contêm uma estrutura tardoz de suporte e fixação à fachada, na qual são suspensos os módulos ajardinados. Os módulos são na sua maioria caixas rígidas preenchidas com meio de crescimento. Algumas soluções modulares assemelham-se a sistemas de vasos, em que cada planta é inserida individualmente numa reentrância.

Os *jardins verticais* são compostos por telas leves com compartimentos para sustentação das raízes das plantas. Neste contexto, destaca-se a composição do sistema desenvolvido pelo botânico Patrick Blanc que é constituído por um painel de policloreto de vinil (PVC) com um centímetro de espessura, fixo à superfície vertical através de uma estrutura metálica ou instalado numa estrutura autónoma. O painel de PVC é coberto com tela geotêxtil tecida de poliamida resistente às raízes e um feltro permeável armado com uma membrana plástica, no qual são criadas pequenas bolsas para inserção das plantas. Este sistema possui a vantagem de ser muito leve, com um peso inferior a $30Kg/m^2$ e de facilitar a cobertura de grandes superfícies, não necessitando de soluções de remate complexas [26].

Drenagem

As fachadas verdes tradicionais habitualmente não possuem um sistema de drenagem, atendendo a que as plantas são enraizadas diretamente no solo. Contudo, no caso de se utilizarem vasos suspensos ao longo da fachada é importante garantir que estes são perfurados por forma a permitir a escorrência da água excedente evitando o encharcamento do substrato.

Os sistemas modulares são os que possuem um modelo de drenagem mais complexo. Frequentemente, as estruturas de suporte possuem diversas furações de drenagem, não só na base mas também nas faces laterais da estrutura, permitindo o escoamento da água excedente para os módulos situados imediatamente abaixo e favorecendo o arejamento e a eliminação do excesso de humidade contida no substrato. A base das peças é usualmente curva ou inclinada para favorecer a drenagem. Para evitar a perda de substrato através das furações de drenagem pode aplicar-se uma tela filtrante (e.g. TPO), que evite a passagem de partículas finas.

No caso dos jardins verticais a própria membrana geotêxtil ou tela de polietileno, ao ser permeável, drena a água e os nutrientes para fornecimento de todas as plantas, não sendo necessário um sistema complementar de drenagem. Tanto nos sistemas modulares, como nos jardins verticais, pode aplicar-se uma caleira na base do sistema, para reunião da água excedente, a qual pode estar ligada ao sistema de drenagem das águas pluviais ou a um depósito para recirculação da água de irrigação.

Meio de crescimento

Caso se trate de um sistema de fachada verde em que a vegetação é enraizada no solo não há a necessidade de incorporar um meio de crescimento no sistema, pese embora o substrato existente possa ser melhorado para corresponder às necessidades das plantas.

Os sistemas modulares integram um meio de crescimento leve, o qual pode ser total ou parcialmente orgânico ou inorgânico. Algumas soluções preveem a instalação de uma camada composta por fibras minerais, que favoreça o enraizamento das plantas, inserida no interior do módulo, onde os nutrientes são fornecidos através do sistema de irrigação. A instalação de um meio de crescimento inerte ou não degradável pode ser favorável por não obrigar a uma substituição tão frequente dos módulos, contudo, isso leva a um maior consumo de água no sistema de irrigação para compensar a falta de nutrientes.

No caso dos sistemas de *paredes vivas*, quer sejam *sistemas modulares* ou *jardins verticais*, as plantas podem funcionar num meio hidropónico, em que os nutrientes são fornecidos pelo sistema de irrigação. Neste caso as plantas são inseridas em bolsas de feltro permeável que sustentam o desenvolvimento das raízes.

Vegetação

A utilização de espécies vegetais em fachadas ajardinadas é muito variável em função do tipo de sistema e local em que este é implantado. Para que este tenha viabilidade importa determinar as condições locais (e.g. exposição solar, sombras projetadas, pluviosidade, ventos dominantes) e as condições de acessibilidade da superfície a revestir, ponderando qual a melhor solução no processo de instalação, manutenção e substituição do sistema.

Nos sistemas de *fachadas verdes* é frequente utilizarem-se plantas trepadeiras, as quais podem ser classificadas como: trepadeiras auto-trepadoras (e.g. P*arthenocissus Tricuspidata e Quinquefolia, Hedera Helix, Hydrangea Petiolaris, Virginia*); trepadeiras com crescimento entrelaçado (e.g. *Wisteria, Kiwi, Buganvília, Dulcamara Americana, Ipoméia, Madressilva, Glicínia americana, Amarelinha*) ou trepadeiras com rebentos (e.g. *Vitis, Aristolochia, Wisteria, Clematis*) [24]. Na aplicação de plantas trepadeiras há que ter atenção às raízes das plantas, que ao se fixarem à superfície vertical podem deteriorá-la, e ao seu processo de desenvolvimento, para que se possa obter o efeito de cobertura desejável.

O uso de plantas trepadeiras constitui uma solução económica de revestimento de superfícies verticais, contudo a escolha das plantas depende das suas características e o local de implementação. Devem utilizar-se plantas trepadeiras autoportantes ou que necessitem de estrutura de apoio, tolerantes ao vento, calor, seca e gelo (e.g. plantas sarmentosas, trepadeiras volúveis e arbustos escandentes).

As plantas trepadeiras podem ser de folha perene ou caduca. As plantas de folha perene mantêm as suas folhas ao longo de todo o ano, protegendo a superfície dos agentes externos como a radiação ultravioleta, intensidade do vento, chuva ou neve. As plantas de folha caduca perdem as suas folhas no outono, alterando a sua imagem ao longo do ano, permitindo que a radiação solar seja absorvida pelas paredes no período de aquecimento.

Quando se pretende revestir grandes superfícies as trepadeiras podem não ser a melhor solução. Estas possuem restrições no seu desenvolvimento, ascendendo até uma altura limitada. Algumas atingem entre 5 a 6 metros, outras 10 metros e apenas algumas espécies atingem 25 metros de altura [16].

Cada vez mais se opta pela utilização de uma maior variedade de espécies adaptadas e de folhas perenes, para que se mantenha o efeito estético da fachada ajardinada ao longo de todo o ano. Inclusivamente têm vindo a surgir diversas soluções onde a variação cromática, a textura e a mutabilidade ao longo do ano são enfatizadas, podendo elaborar-se desenhos com a própria vegetação ao longo da fachada.

Alguns sistemas possuem também uma grelha ao longo da qual se desenvolvem algumas espécies de trepadeiras cujo crescimento deve ser devidamente controlado.

No caso dos *sistemas modulares* com meio de crescimento a revestir todo o módulo podem aplicar-se outras variedades de plantas, desde gramíneas, *Sedum* e espécies com raízes pouco profundas. Estes sistemas podem ser pré-plantados ou pré-semeados com as espécies selecionadas, correndo-se um menor risco de a vegetação não vingar.

Nos *jardins verticais* pode aplicar-se uma grande variedade de plantas, no entanto a sua seleção deve ter em conta as condições do local e a capacidade de resistência a meios hidropónicos.

Irrigação

As fachadas ajardinadas pela sua configuração e implantação tendem a necessitar de um meio complementar de irrigação. A água é fornecida em pontos estratégicos, devendo atingir toda a superfície vegetal por efeito gravítico.

Nas *fachadas verdes* pode evitar-se a instalação de um sistema de irrigação, desde que a base das plantas se localize numa área acessível para executar a rega manual.

Nos sistemas *modulares* é frequente optar-se pela instalação de uma tubagem de irrigação perfurada fixa a uma reentrância situada na face superior dos módulos. A água penetra no meio de crescimento inserido nos módulos e percorre toda a superfície vegetal por gravidade. A intensidade e distribuição da irrigação devem ser adaptadas às necessidades das plantas instaladas e às condições climáticas. A água para irrigação pode ser melhorada com nutrientes, no entanto deve evitar-se o uso de químicos poluentes.

Os *jardins verticais* hidropónicos são habitualmente sistemas com elevado consumo de água, que pela inexistência de substrato, necessitam da adição de nutrientes no sistema de irrigação para suprir as necessidades das plantas.

Benefícios dos revestimentos ajardinados

Num contexto mais abrangente, são vários os autores que referem os benefícios das coberturas e fachadas ajardinadas no contexto urbano como medidas que contribuem para fomentar a sustentabilidade dos meios urbanos.

A vegetação possui a capacidade de melhorar a qualidade do ar [9], ao absorver os gases poluentes [27], ao suster as poeiras suspensas no ar e libertar oxigénio.

A inserção de áreas ajardinadas de dimensão considerável no contexto urbano fomenta a mitigação do "efeito de estufa", pois contribui para o arrefecimento das superfícies e para o aumento dos níveis de humidade no ar.

As soluções de coberturas e fachadas ajardinadas possuem a vantagem de contribuírem para a introdução de vegetação no contexto urbano, aumentando a biodiversidade sem qualquer ocupação do solo, o que pode ser vantajoso em áreas urbanas onde há escassez de espaços livres, permitindo introduzir a natureza na vida diária dos cidadãos [26].

É também importante ressalvar a componente estética das coberturas e fachadas ajardinadas no contexto urbano, quer pelas qualidades visuais que incorporam (variedade cromática, textura e mutabilidade), quer pelas possibilidades de requalificação urbana de áreas consolidadas. Com base nestes sistemas podem conferir-se novos usos através da instalação de espaços ajardinados em coberturas transitáveis existentes, ou melhorar o enquadramento urbano através da instalação de fachadas ajardinadas, ocultando empenas deterioradas, garantindo alinhamento de fachadas, regularizando as cérceas de uma frente urbana ou mesmo reforçando a intimidade em pequenos espaços privados exteriores [28].

A vegetação é reconhecida pelo seu efeito terapêutico, melhorando esteticamente e visualmente os espaços em que se insere, daí que o atual mercado valorize a qualidade do imobiliário através de fatores como a vista e a proximidade com ambientes naturais e de lazer (e.g. parques, jardins, terraços).

No caso de instalação de coberturas ajardinadas as águas pluviais podem ser absorvidas diretamente pelo substrato, diminuindo a escorrência superficial. Desta forma a cobertura atua como um sistema de purificação, retendo as impurezas e metais pesados contidos nas águas pluviais [8] e reencaminhando a água excedente para o sistema de drenagem. No entanto a capacidade de minimização da escorrência superficial de águas pluviais através de coberturas ajardinadas depende da profundidade do substrato, do tipo de plantas e do padrão de pluviosidade anual [1].

Alguns estudos apontam que estes sistemas podem ser alternativas interessantes em climas frios e quentes, onde os edifícios possuam necessidades elevadas de aquecimento e arrefecimento [29].

A integração de vegetação no edificado permite melhorar a performance da envolvente protegendo-a a dos agentes externos, como a radiação solar direta, ação direta da chuva e do vento, atuando no edificado como um sistema passivo [26], que permite melhorar o conforto térmico dos espaços interiores, quer no inverno quer no verão.

A vegetação possui também a vantagem de sombrear a superfície envolvente [30, 31] e de absorver alguma radiação solar para desenvolver as suas funções vitais (fotossíntese, respiração, transpiração e evaporação), evitando o seu sobreaquecimento e a degradação dos materiais superficiais, tais como as membranas de impermeabilização das coberturas, por ação da radiação solar direta [21, 32, 33].

Diversos estudos foram desenvolvidos recentemente no sentido de avaliar a contribuição das superfícies ajardinadas para a eficiência térmica dos edifícios [34, 35], mediante a medição de dados *in situ*, tais como: temperatura e humidade relativa do ar envolvente, temperatura e humidade superficial, sombreamento, iluminância e velocidade do vento. Estes estudos demonstram que as superfícies ajardinadas absorvem menos radiação solar do que a maioria dos materiais de revestimento [36], o que leva a uma redução da temperatura superficial da envolvente edificada [9, 30, 37, 38, 27] e a uma menor transferência de calor para os espaços interiores [31]. A redução da temperatura superficial resulta também do processo de evapotranspiração das plantas [23, 39, 40] e da humidade contida no substrato. Estes resultados levam a menor consumo de energia dos sistemas de climatização [32, 37, 40], com especial destaque sobre o consumo de energia associado aos sistemas de arrefecimento. Por outro lado, a presença de substrato influencia também a inércia térmica da envolvente [41], cuja espessura garante uma capacidade de armazenar calor, o que pode ser bastante útil no período de inverno.

A integração de vegetação no edificado permite também melhorar o isolamento acústico do edificado [42] e minimizar a propagação sonora em ambientes urbanos [43, 44].

Apesar das diversas vantagens para o edificado e para o contexto urbano, importa salientar que a análise dos benefícios e a adequabilidade dos sistemas de coberturas e fachadas ajardinadas face à realidade construtiva de Portugal, não foram ainda analisados, o que pode ser um tema de estudo com forte relevância.

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Abstract

The construction sector and mining and quarrying industries are the largest waste producers in the European Union, accounting for 35% and 28%, respectively, of the total waste produced. Therefore, it is essential to develop innovative constructive solutions based on the reuse of these wastes to create new materials with added value.

This work presents the design of a modular system for vegetated surfaces with alkaline activation materials (Geogreen). The modular system stands out in the area of building materials, differentiating itself from other existing green roofs and green walls by its constructive characteristics, incorporation of industrial waste materials and integration of sustainability principles.

The results demonstrate that this modular system contributes not only to the aesthetic function of a vegetated surface but also allows improving the thermal and acoustic conditions of the built environment. It contributes to the construction market with a more sustainable solution through the integration of waste materials and energy minimization.

Keywords

Modular system, vegetated surfaces, green roofs, green walls, alkaline activated materials, thermal analysis, building acoustics, life cycle analysis.

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2. Design of alkali-activated materials for a modular green wall and green roof system.
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3. Thermal analysis of a new modular system for green walls.
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5. Modular system design for vegetated surfaces: A proposal for energy-efficient buildings.
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   Tektonica International Fair 2013, May 2013.
4. 2nd best Presentation from Students Session
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Chapter 1

Introduction

1. Definition of topic research

This work presents the concept design of a modular system for vegetated surfaces, green roofs and green walls, incorporating alkaline activated materials (Geogreen). First studies about this modular system result from the Research and Development project “GEOGREEN, Waste geopolymeric binder-based natural vegetated panels for energy-efficient building green roofs and facades”, developed at C-MADE, Centre of Materials and Building Technologies between 2011 and 2014. These studies resulted in the publication of a national invention patent PT106022. The present work follows this research and is supported by the PhD Scholarship SFRH / BD / 98422/2013, funded by the Foundation for Science and Technology under the QREN-POPH / ESF program, co-financed by the European Social Fund and national funds from the Portuguese Ministry of Education and Science.

2. Context

Most urban areas have been increasing their density in an unsustainable way, which reflects in the deterioration of their environmental conditions. The concentration of materials that absorb high amounts of solar radiation leads to the overheating of urban areas, especially at night, a phenomenon known as "greenhouse effect" [1]. At the same time, with the increase of ground waterproofing and lack of permeable spaces, rainwater is not drained naturally, increasing surface runoff and, consequently, creating difficulties to drain rainwater. Another problem that arises from the growth of urban spaces consists in the increase use of the car in urban areas, which is reflected in high pollution levels and deterioration of air quality.

The integration of vegetation can be an important contribution to solve these problems, benefiting both the urban context and buildings environment. The use of vegetation in the built environment has been proven to have several environmental, social and economic benefits, which has led to a growing research on this theme. Also the Horizon 2020 Final Report reports the use of Nature Based Solutions, as a strategy to create more sustainable and resilient societies [2].

The EU Energy Performance of Buildings Directive (EPBD) [3] mentions that by 2020 all new buildings must be nearly zero-energy. The aim of this initiative is to promote the energy performance improvement of new and existing buildings subjected to major renovations, minimizing their energy dependency and greenhouse gas emissions. Therefore it is important to increase the use of efficient heating and cooling systems, renewable energy sources and passive design solutions, like green walls and green roofs.

It is also important to mention that the construction sector and mining and quarrying industries are the largest waste producers in the European Union, accounting for 35% and 28%, respectively, of the total waste produced [4]. Therefore, it is essential to develop innovative constructive solutions based on the reuse of these wastes to create new materials with added value.

This work has the purpose to demonstrate how mine waste materials and other recycled materials can make part of new system for vegetated surfaces and how the characteristics of the system itself can contribute as a sustainable strategy to improve buildings comfort.

3. Statement

This thesis proposes a new approach in the field of green roofs and green walls with regard to the design of an innovative modular system, considering the type of materials used and its constructive characteristics.

The design of this system aims to integrate principles of sustainability. It integrates solutions that minimize the consumption of natural resources, promotes the use of waste and recycled materials in their composition and the reduction of irrigation needs, through the absorption and retention of water and the use of plants adapted to the local climate. An evaluation of this modular system environmental impact is also proposed allowing to find strategies to minimize the system embodied energy.

This system also aims to increase the comfort of the interior spaces contributing to improve the thermal and acoustic characteristics of buildings envelope.

4. Main goals

This work aims to study the development of a modular system for green walls and green roofs based on the following:

- Search for traditional solutions and new designs of existing roofing and facade systems and systematize their features and benefits;
- Identify solutions for the integration of greening systems in the urban context;
- Design a modular system for vegetated surfaces promoting the use of alkaline activation materials obtained from waste and other natural and sustainable materials;
- Study the composition of each layer of the proposed modular system;

- Systematize and detail the system considering the restrictions of horizontal or vertical positioning, allowing its installation in new buildings or in the rehabilitation of existing buildings;
- Calculate the number and type of support elements for the modular system and identify the best support solution for this purpose;
- Perform a cost analysis of the system, establishing a comparison with other conventional systems for the same purpose;
- Perform laboratory tests to evaluate the physical characteristics (compressive strength, water absorption by capillarity rise and density) of alkaline activation mixtures in order to identify the composition that best suits the modular system;
- Test thermal performance parameters of the modular system for green walls by performing *in situ* measurements in a location with real climate conditions;
- Test acoustic performance parameters of the modular system;
- Conduct a life cycle analysis of the modular system to evaluate the sustainability of the system with regard to the choice of materials and production process;
- Analyse the obtained results, establish recommendations for improvement and present possible future developments.

5. Methodology

At first was developed a research of current and innovative solutions of green roofs and green wall, namely, some of which are not yet on the market and only have their patents published. This was followed by the analysis of how these systems can contribute to urban design.

Based on the lessons learn from existing green roofs and green wall solutions, a design solution was developed for the proposed modular system for vegetated surfaces. The concept design was followed by the development of several studies related to the properties of this system to be applied as greening system, which resulted in the publication of scientific articles. In this context, alkali-activated materials properties were tested to improve its suitability to the proposed modular system. Also, some thermal and acoustic benefits of this system were evaluated. Finally, a comparative study was developed on the life cycle analysis of the new modular greening system.

6. Main Contributions

State-of-art of green roofs and green walls

This work aims, in a general context, to complement the knowledge in the field of vegetated surfaces, namely green roofs and green walls. For this purpose, a systematization of the existing systems and analysis of their constructive characteristics are presented. This work also includes a bibliographical review of the benefits associated to these greening systems, both for the urban context and for the built environment.

Design of a modular system for vegetated surfaces

This work presents the design of a modular system to create vegetated surfaces in new and existing buildings. It aims to be of simple assembly and disassembly to create vegetated surfaces quickly and effectively. It can be adaptable to different surfaces and inclinations, allowing its application in the construction or rehabilitation of roofs, facades and other built elements.

This work explores new possibilities of designing modular elements for green roofs and green walls using new shapes and geometries through moulding, CNC cutting and milling. The modular elements can acquire different configurations and inclinations according to the needs of application and architectural context.

From this work resulted a specific configuration which was subject of further study of its constructive characteristics, support elements and its materials. Each module includes a base made of a porous and resistant alkaline activation material, a light upper element made of insulation cork board, and endemic plant species. The fastening system of these modular elements is calculated with the aim of providing their application both in roofs and walls, and also to minimize the number of support elements per piece.

Application of alkaline activation materials in vegetated surfaces

This work demonstrates an evolution in the knowledge of alkaline activation materials and considers their integration into new architectural applications, namely in a modular system for green roofs and green walls.

The presented modular system distinguishes itself from others through the integration of alkaline activated waste materials in its composition. The tests for new compositions of alkaline activated materials (geopolymers) are based on mixtures that reuse industrial waste (Panasqueira mines and recycled glass) and the addition of several aggregates. This study is based on the equipment and knowledge available in the C-MADE Research and Development unit, about alkaline activation mixtures using mine waste and other materials.

Recent studies have shown that mud waste from Panasqueira mines has a high alumino-silicate composition and is considered a very promising material for the production of alkaline activation materials, both from an environmental and economic point of view. Alkaline activation materials (also known as geopolymer binders) obtained to date has high compressive strength, good abrasion resistance and acid resistance. It is important to mention that those studies demonstrate that the leaching of heavy metals from alkaline activation materials obtained from Panasqueira mines mud waste is very small, demonstrating that alkaline activation as a very safe process of encapsulating these metals [5] [6].

The alkaline activation mixture to be used as reference was subjected to several combinations in order to obtain a blend with the best compressive strength results. In this context, several percentages of each precursor (mud and glass), different curing temperatures and molar concentration of sodium hydroxide were tested. After defining the reference mixture several types of aggregates (sand, expanded cork granules and expanded clay) were added with the intention of maximizing its water absorption capacity and minimizing the mixture density, keeping an appropriate compressive strength for this purpose.

Improvement of thermal and acoustic conditions of buildings

In addition, real-scale prototypes were created to evaluate how this modular system for vegetated surfaces can contribute to improve the thermal and acoustic performance of buildings envelope.

The thermal analysis is developed along different periods in an exterior test cell through comparison of interior surface temperatures and heat flux between a reference wall and a wall covered with the modular system in identical conditions.

The acoustic evaluation of this modular system is based on the identification of how factors such as substrate, plants, their variety and height affect sound absorption in simulated conditions.

Strategies to minimize environmental impact

This work also focuses on the integration of sustainability strategies in the system development. The application of alkaline activation materials results from the aim of promoting waste recycling and reuse, contributing to the minimization of the consumption of natural resources. The integration of these materials functions as a strategy to absorb water and transmit it slowly to the plants. The use of vegetation adapted to the local climate simultaneously aims to minimize the need for irrigation, while contributing to the retention of carbon dioxide.

The application of insulation cork board (ICB) in the modular system results from the intention of using sustainable materials with a low environmental impact. In addition, this material has thermal and acoustic properties that can contribute to the environmental comfort of built spaces.

A comparative life cycle analysis (LCA) was developed to evaluate the long term environmental benefits of this system considering a "cradle to gate" approach. This study compared different environmental factors, identifying which processes involved higher energy consumption. This analysis allowed implementing new strategies to reduce the embodied energy of this system and consequently its CO_2 emissions. This solution was also compared with other systems to better evaluate its impact on different categories.

7. State-of-art

Vegetated surfaces are a broader concept which includes all types of greening systems, like green walls and green roofs. A literature review led to the identification of the benefits of vegetated surfaces and vegetation itself to urban environment and buildings envelope. This study took into consideration also led the classification and definition of all types of green roofs and green walls.

7.1 Historical context

Greening has always marked its presence in buildings. Emphasis is placed on emblematic examples such as the Suspended Gardens of Babylon, based on terraced buildings full of vegetation around them. Other notable examples refer to the Greek and Roman Empires where vines, chestnut trees and olive trees [7] were used to shade buildings. In Scandinavian countries, such as Iceland and Norway, sod roofs or turf roofs are part of the vernacular architecture [8]. In fact, some of these buildings remain until today.

Green roofs are an ancient practice, but it was in Germany during the 1960s and 1980s that research on extensive green roofs was intensified and widely used to control rain in densely populated areas [9]. In the following decades, a number of German government initiatives encouraged the application of green roofs, reaching to about one million square meters of green roofs in 1989 and reaching to about ten million square meters of green roofs in 1996 [10]. Some of these examples still remain in good condition, which serves as an indicator of the durability of the implemented solutions. At the beginning of the twentieth century green roofs were also of the architectural avant-garde and integrated into projects by Le Corbusier, Walter Gropius and Frank Lloyd Wright [11]. Recently, in some US cities some incentives have also been introduced for the installation of green roofs as a measure to promote sustainability in the urban context [1].

In the seventeenth and eighteenth centuries the use of vines on facades of European buildings became common [8] and later in the nineteenth century this solution expanded to the United States of America. In the 1980s the use of climbing plants in walls intensified, mainly in Germany, where incentive programs were set up to install green façades. According to Manfred Köhler, it is estimated that in Berlin, between 1983 and 1997, about 245 584m^2 of garden façades were installed [9].

Green roof systems have been widely used. However, the application of living walls is a newer technique which has been evolving in the latest years. At present, the market is adapting to new demands, looking for innovative and more efficient solutions for green roofs and green walls.

7.2 Benefits of vegetated surfaces

In a broader context, several authors mention the benefits of green roofs and green walls as a strategy to implement sustainable principles in the urban context.

Vegetation has the capacity to improve air quality [9] by absorbing CO_2 [12] and retaining dust particles suspended in the air [9, 13] while releasing oxygen.

The inclusion of large green areas in the urban context encourages the mitigation of the "greenhouse effect", as it contributes to surfaces cooling and increasing levels of humidity in the air.

Green roofs and green walls contribute to introduce vegetation in the urban context, increasing biodiversity without any land occupation [14], which can be advantageous in urban areas where there is scarcity of free spaces, introducing nature in the daily life of citizens [15].

It is also important to emphasize the aesthetic component of green roofs and green walls in the urban context. Both for the visual qualities they incorporate (chromatic variety, texture and mutability) and for the possibilities of urban requalification of consolidated areas. Based on these systems, new uses can be made through the installation of landscaped spaces in existing roofs, or improving the urban setting through the installation of green walls [14].

The vegetation is also recognized for its therapeutic effect, improving aesthetically and visually the spaces in which it is inserted, hence the current market value the quality of real estate through factors such as the view and proximity to natural and leisure environments (ie parks, gardens , terraces).

In the case of green roofs, rainwater can be absorbed directly by the substrate, mitigating surface runoff. Also green roofs act as a purification system, retaining the impurities and heavy metals contained in rainwater [8] and rerouting the surplus water to the drainage system. However, the surface runoff of rainwater in green roofs depends on the substrate depth; the type of plants and the annual rainfall pattern [1].

Some studies indicate also that these greening systems may be interesting alternatives in cold and hot climates where buildings have high heating and cooling needs [16].

The integration of vegetation in buildings allows improving their performance while protecting buildings envelope from external agents, such as direct solar radiation, direct action of rain and wind, acting as a passive design system [15].

Vegetation also has the advantage of shading buildings envelope [17, 18] and absorbs solar radiation to develop its vital functions (photosynthesis, respiration, perspiration and evaporation). This avoids overheating and degradation of surface materials, like roofs waterproofing membranes, by incidence of direct solar radiation [19, 20, 21].

Also, recent studies demonstrate the benefits of vegetated surfaces, like green walls and green roofs, to buildings performance (Figure 1).

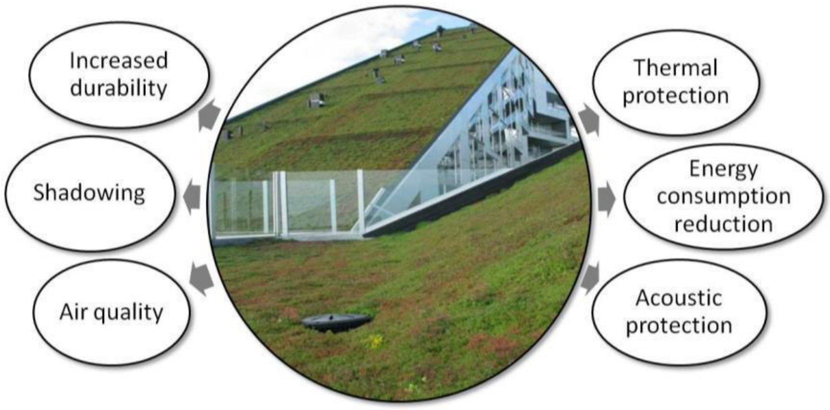

Figure 1 - Benefits of vegetated surfaces to buildings performance

Several studies have been developed recently to evaluate the contribution of vegetated surfaces to the thermal performance of buildings [22, 23].

Green surfaces absorb less solar radiation than most cladding materials [24], which leads to a reduction of the surface temperature of buildings envelope [9, 25, 26, 17, 12] and to a smaller heat transfer to indoor spaces [18]. The reduction of surface temperature also results from the evapotranspiration process of plants [27, 28, 29] and moisture contained in the growing medium. These effects have a positive influence on the energy consumption of air conditioning systems [20, 25, 29]. On the other side the presence of substrate may have influence on the thermal inertia of buildings envelope [30], having the ability to retain heat, which can be relevant in the heating period.

The integration of vegetated systems in buildings also contributes to improve their acoustic performance [31] and minimize sound propagation in urban environments [32, 33].

7.3 Promoting the application of vegetated surfaces

It is an emerging challenge to expand, qualify and diversify the green urban structure to create more sustainable cities for citizens (in environmental, economic and socio-cultural terms) [34]. Several North American cities such as Chicago, Portland, Philadelphia, or Toronto recognize the benefits of greening new and existing buildings and have created incentives for the installation of green roofs [35].

Similar strategies have been spreading across Europe, as in Copenhagen [36] or City of London [37]. Also in the Oriente, Singapore, despite its high urban density, already includes 100 hectares of landscaped coverings, between roofs and green walls. Singapore aims to double this area until 2030 through the Skyrise Greenery Incentive Scheme Program. In order to promote the application of vegetated systems, this program also includes guidelines to inform the participants about the correct installation of vegetated systems and their correct maintenance.

At present, the market is adapting to new demands, looking for innovative and efficient solutions of green roofs and green walls. Green roof systems have been widely disseminated. However, the promotion of the application of living walls is still growing.

7.4 Vegetated surfaces as elements of urban regeneration

In the contemporary city, the scarcity of green and recreation spaces is coupled with the use of large-scale waterproofed surfaces. Green roofs and green walls can be a differentiating factor in buildings, improving their environmental comfort, creating green spaces without land occupation, qualifying buildings image and constituting an amenity at all scales [38].

The insertion of green roofs in buildings can be carried out at several scales, From an individual, private space as a balcony (Figure 2, left), to a building roof (Figure 2, middle) or a landscaped terrace between buildings (Figure 2, right).

Figure 2 - Private terrace, Torre Verde, Lisboa [39] (left); The 8 Tallen, Copenhagen (September 2012) (middle); Footpath, Copenhagen (September 2012) (right).

Green walls and green roofs can be used as elements of urban composition and urban design. Green walls can be used as refined elements in order to promote the harmony in between different buildings heights (Figure 3, left). As an example the green wall project of Patrick

Blanc in Pacha-The Driver, London shows an innovative way of marking buildings height, along both sides of adjoining buildings, which are markedly different between two streets (Figure 3, right). Also, when the alignments between adjoining buildings are different, green walls can also be used to rectify this aspect (Figure 4). Also, often blank walls in buildings reveal an unplanned urban development, resulting in an unqualified image of the place. This can be minimized with the application of living walls, making the public space more stimulating for users (Figure 5, left). Significant examples are the cultural building CaixaForum, Madrid, Spain (Figure 5, right) and the regeneration of a blank wall along one side of the street Rue d'Alsace in Paris, France. A vertical garden covers the blank wall of the existing buildings. As a result, both buildings gain a further qualified image. The urban environment of these spaces are greatly improved, making more pleasant public space for citizens and reinforcing the sense of security amongst users. Green walls can also help reinforcing the sense of intimacy in small spaces (Figure 6, left). A good example of this particular benefit is the integration of a vertical garden on the fence wall that encloses the inner courtyard of the Royale Café in Lisbon, Portugal (Figure 6, right). This solution allows this small private space to have green elements, providing a more welcoming, friendly and cozy environment for customers [40].

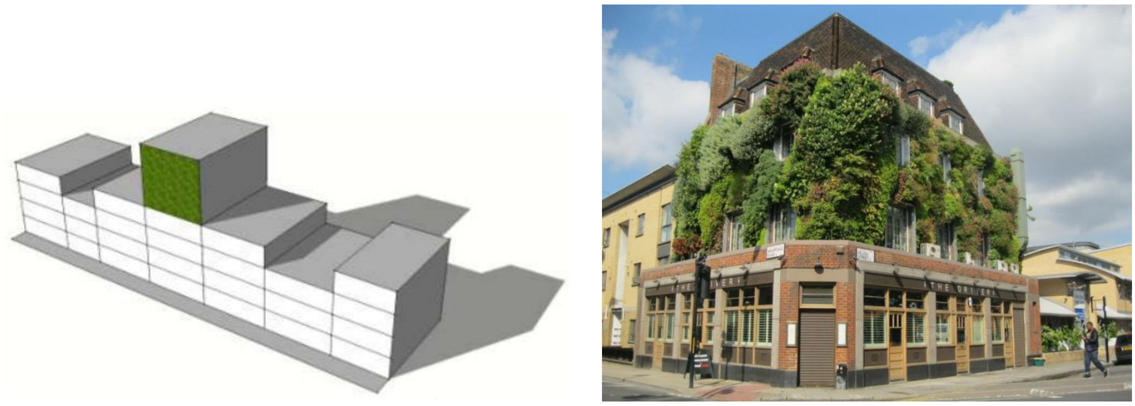

Figure 3 - Level buildings height with green walls (left) Pacha- The Driver, London, United Kingdom (August 2011) (right).

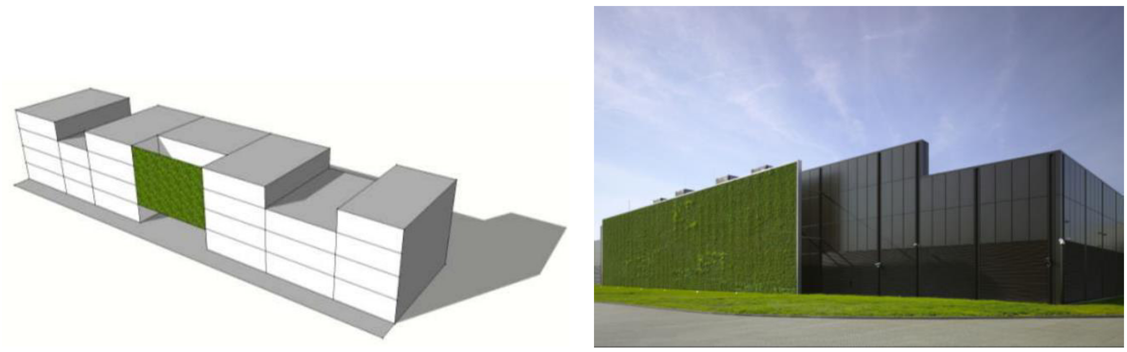

Figure 4 - Adjusting buildings alignment with a green wall (left) Citi Data Center in Frankfurt, Germany [41] (right).

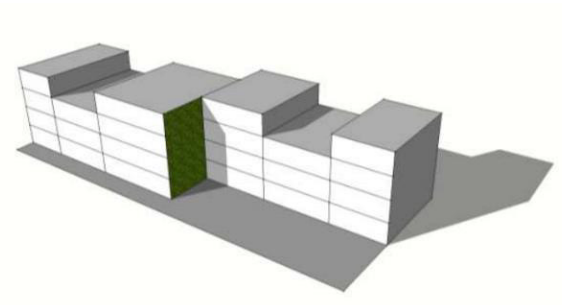


Figure 5 - Masking a blank wall with a green wall (left) Caixa Forum, Paseo del Prado in Madrid, Spain (June 2011) (right).

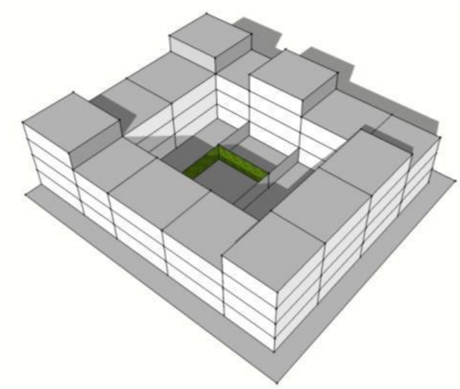


Figure 6- Green wall in an interior courtyard (left); Royale Café in Lisbon, Portugal [42] (right).

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Chapter 2

Green roof systems: A review of their characteristics

1. Introduction

In order to better identify and systematize green roof systems it is important to analyse their composition by layers and function and classify them according to their main technical characteristics.

2. Classification and definition

Green roofs are usually classified according to their layers. There are 3 main types of green roofs: extensive, intensive and semi-intensive (Figure 1).

Extensive green roofs are lightweight systems that can be installed in existing, flat or sloped roofs up to 30° [1]. Due to their thickness they have limitations on the type of plants to be used. Although systems thickness limits the type of plants to be installed, they can be a good solution to improve the aesthetics of non-accessible roofs without overloading the building structure [1]. Extensive green roofs are systems without major technical difficulties of installation, requiring only occasional irrigation and maintenance. Alternatively, non-conventional systems may be applied in walkable areas such as terraces, balconies, patios or porches [2, 3, 4, 5, 6].

Intensive green roofs are usually applied in roofs with higher load capacity and sufficient depth to install a layer of substrate that allows the development of grasses, shrubs and small and medium-sized trees. By containing a layer of substrate of greater thickness, it allows a higher contribution to the thermal and acoustic insulation of the surface. However, these systems require regular irrigation and maintenance [1].

Some authors refer to the existence of a third classification, the semi-intensive green roofs [7]. These systems have intermediate characteristics, aiming to incorporate characteristics of the extensive and intensive systems [8]. These systems contain an intermediate thickness, allowing the integration of a greater number of plant species than extensive systems and minimizing maintenance and irrigation needs when compared to Intensive systems.

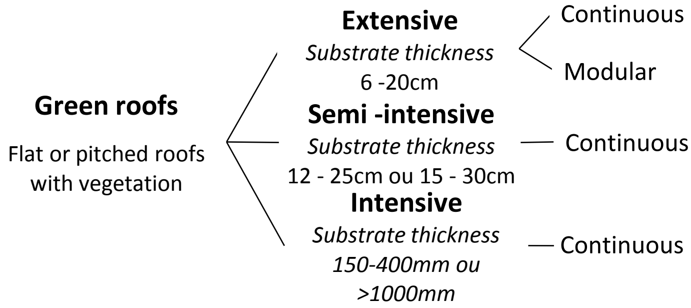

Figure 1 – Green roof systems [9].

In the context of extensive green roofs, alternative solutions have emerged, such as modular systems (Figure 2 left) and pre-rooted continuous systems (Figure 3). These are systems with advantages of installation that allows creating vegetated surfaces in a shorter period of time. The lightness of these solutions and the possibility of replacing modular elements also make maintenance and repair easier and quicker.

Most modular green roof systems consist of a plastic or metal container filled with growing medium to allow the development of the plants. These modules have in their majority a quadrangular configuration whose size and weight allow the proper handling of the system for maintenance purposes. The modules can be executed in one piece or have a number of elements that fit together [2] and have side fittings to ensure the system continuity.

Some solutions, both modular and continuous, foresee not only the installation in flat roofs but also in pitched roofs. In these cases there must be an element that supports the green roof, encouraging plants rooting and preventing the substrate from slipping (Figure 2, right).

Figure 2 – Modular extensive green roof (left) and substrate support mesh for pitched roofs (right) [10].

Figure 3 – Pre-grown vegetation blanket for extensive green roofs (left) [11]; vegetation mat with reinforcing net (right) [12].

Continuous green roofs usually include a set of layers to protect the support and improve the system performance (Figure 4). The most common layers are: waterproofing layer, anti-root layer, drainage layer or membrane, filter layer, growth medium and vegetation. These elements can be placed over an existing or proposed structure. These layers must be placed over a filling layer with a minimum slope of 1.5 to 3%, to be able to drain excessive rainwater along the roof. The support must also be waterproofed before proceeding to the green roof installation.

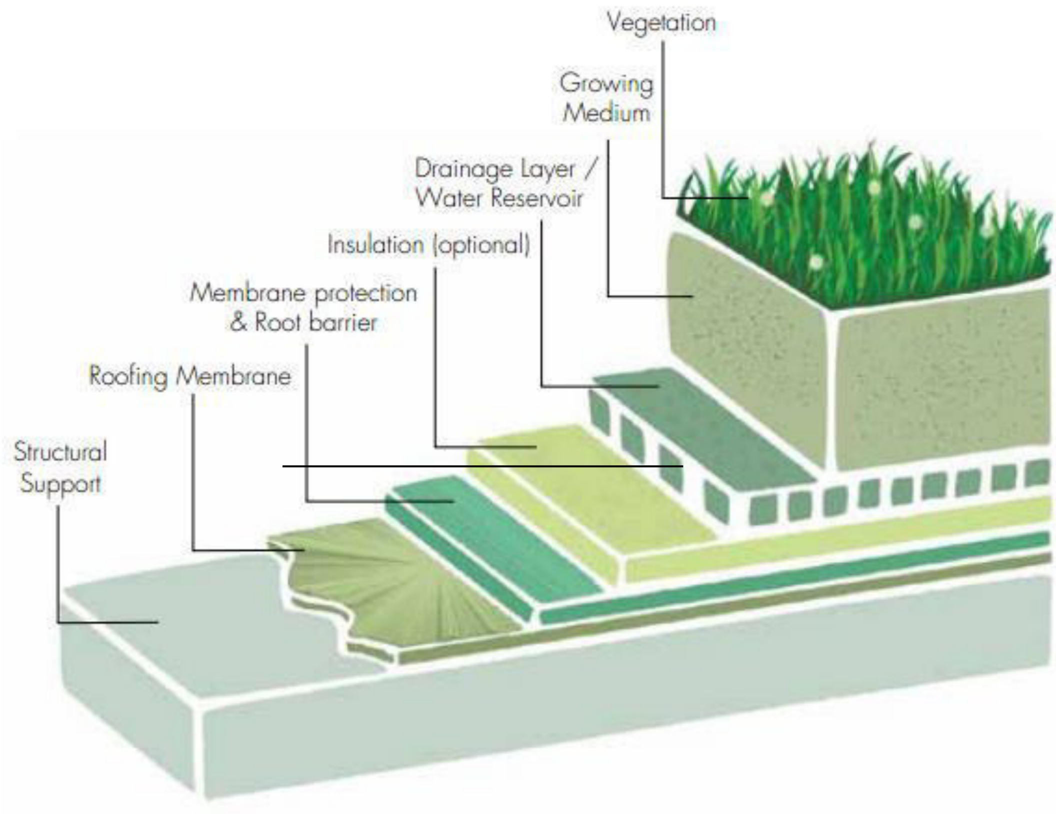

Figure 4 – Conventional extensive green roof layers [13].

The current innovation of extensive green roofs focuses mainly in modular systems. Modular elements are often reinforced on the sides and back to be able to support the saturated growing medium load. They can also have side grooves to ensure the system continuity or handles to help lifting them [14] (Figure 5). Some configurations are also stackable to simplify their transport. These systems can also provide the possibility to remove modular elements individually for roof maintenance or vegetation replacement.

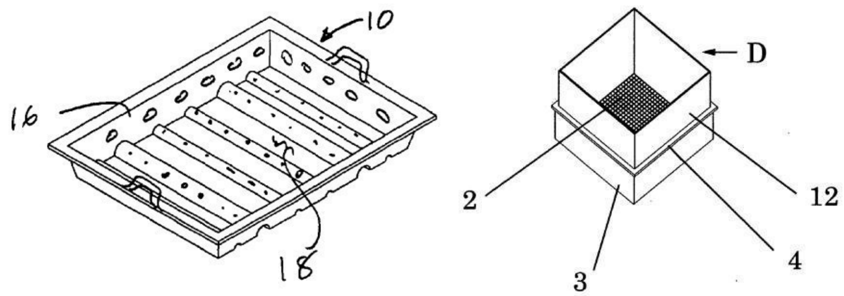

Figure 5 – Patent US 2002/0007591 A1 [14] (left); Patent US 2007/0101646 A1 [4] (right).

Others have an extender collar to increase the growing medium depth and allow the installation of a larger variety of plants [4, 15] (Figure 6). Most of the analysed modules contain a textured base with deposits for excess water accumulation and distribution channels along the surface (Figure 6). The modules back and sides may have holes to drain excess water and avoid drenching the growing medium. To prevent clogging some examples include anti-root netting to cover the bottom of the modules.

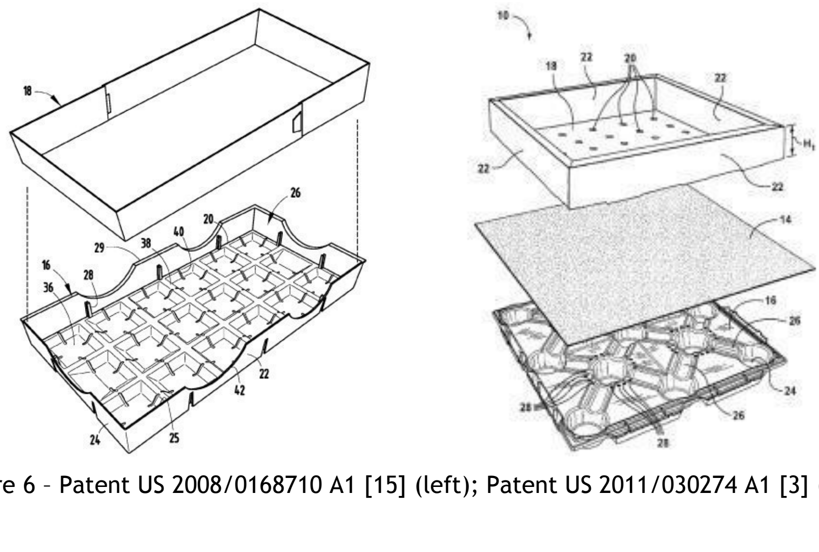

Figure 6 – Patent US 2008/0168710 A1 [15] (left); Patent US 2011/030274 A1 [3] (right).

To make green roofs lighter, flexible and guarantee lower costs, polymeric materials are often used. These can be transported to the roof manually, in rolls, and are easy to apply [16]. The sustainability of green roof systems is still a very recent concern. Only some occasional examples propose the use of recycled or recyclable materials, like recyclable high density polypropylene [17], recycled rubber [14] or recycled carpet [18]. Also the use of natural and biodegradable materials is mentioned like using single or double corrugated cardboard with an impermeable film based on vegetable oil or corn starch, to retard the container degradation [3].

Modular solutions can simplify roof maintenance however the lack of continuity between modules creates problems of water distribution, requiring a more complex irrigation system and making more difficult to distribute drained water between modules. Also the gaps between modules create variations in the thermal conductivity of the surface.

3. Systems requirements

3.1 Thermal insulation

Depending on the type of system and substrate layer thickness, it may be necessary to apply a thermal insulation layer. There are some systems in which this layer is under the waterproofing layer and others, called "inverted systems", in which the insulation is installed over the waterproofing layer [19].

3.2 Waterproofing

The roof structure on which the green roof is build must be adequately waterproofed to prevent water infiltration. The waterproofing system must also ensure the dilation and contraction of the structure without breaking, to prevent water penetration. Anti-roots chemical additives can be added to this layer or an anti-root layer can be added.

3.3 Drainage

Extensive green roofs usually include a light drainage membrane, in polymeric material, with a three-dimensional matrix of semi-conical recesses (which size is defined by the manufacturer). This layer receives the excess water contained in the substrate and accumulates it in small deposits, avoiding substrate drenching and root rot. This layer retains water and also drains the excess to the rainwater drainage system. Some solutions include two geotextiles on the top and bottom faces of the drainage membrane. The laminated felt on the underside protects the waterproofing system and the upper felt serves as a filter screen.

In the case of intensive green roofs, the drainage layer must have higher load capacity. In these solutions it is common to use aggregates whose density can exceed $8kg/m^2$ per centimetre of depth [20].

3.4 Anti-Root Screen

The anti-root screen aims to prevent the roots penetration. In the market there are two types of systems, chemical and physical anti-root systems [16]. Physical systems are usually polymer screens that can be applied on top of the building structure. Chemical systems are based on the use of toxins, like copper embedded in the waterproofing screen, preventing roots proliferation.

3.5 Filter screen

The filter screen is usually applied below the substrate layer to prevent migration of small particles that may eventually block water drainage. Usually, low weight and reduced thickness screens are used. This can be fixed directly to the drainage layer [16]. For this purpose, it is frequent to use porous but puncture resistant materials formed by non-woven fabrics of synthetic fibres.

3.6 Water retention

In addition, a water retention layer may be applied. It can absorb rainwater or irrigation water and slowly release it to the substrate. The need for water retention can be very variable depending on: local climate conditions; type of system - extensive or intensive; vegetation needs and growing medium characteristics.

3.7 Growing medium

The growing medium provides the nutrients necessary for the development of plants and means for roots proliferation. This may be composed of inorganic and organic elements or by the combination of both. Several substrate compositions can be made, from industrial mixtures analysed for specific purposes, to mixtures customized according to the type of system and plants to be installed. The most appropriate growing medium mixture must be a balance of its thickness, weight and plants requirements.

The growing medium used in extensive systems is usually based on the application of low density substrates made from mixing organic particles with inorganic particles and can be improved with other nutrients added to irrigation water. In addition, non-woven materials can be used to favour plants rooting, anchoring and function as water retention.

3.8 Vegetation

Vegetation selection in green roofs is strongly conditioned by the support, namely with regard the substrate thickness and roof load capacity. In fact environmental conditions at building level are different from ground conditions, reason why vegetated surfaces can integrate a restricted number of species [21], taking into account the context in which they are inserted. The vegetation should be adapted to both the type of system and local climate. Green roofs are usually exposed to extreme climatic conditions (i.e. permanent sun exposure, strong winds, among others) and have a limited substrate layer for the development of roots with a finite amount of nutrients, which can also determine the irrigation needs.

Intensive green roofs support several types of plant species. For surfaces with thicknesses over 15 cm or 20 cm, grasses and shrubs weighing around 10 kg/m^2 may be applied. In areas with thicknesses greater than 0.90m it is possible to apply all the species mentioned above and even shrubs with around 20 kg/m^2 or even small trees [20].

For extensive green roofs, several studies indicate the use of succulent plants (i.e. *Sedum*). This type of vegetation has high resistance to extreme climatic conditions and low weight, usually under 10 kg/m^2 [20]. Some other vegetation types can also be used in these systems like mosses, grasses, wild flowers, grasses and other species.

The most suitable plants to install on roofs should be resistant to periods of drought and sun exposure and should be adapted to the local climate, in order to minimize irrigation needs.

Modular systems are usually pre-seeded or pre-planted. In the case of continuous systems, sowing or planting on site are commonly used. Alternatively, pre-planted carpets can be used (Figure 3).

3.9 Irrigation

Irrigation needs depend on local climate conditions, the system itself and the type of plants to be installed. In the case of intensive green roofs, irrigation may be fundamental for the development of vegetation.

The irrigation can be made from a drip irrigation systems or sprinklers. Some irrigation systems can also be embedded in modular elements, others are designed to be installed over them.

In this context it is also a concern to minimize water consumption, by installing a rainwater recovery system [22] or even a recycling system of black and grey water that is locally treated and reused to complement irrigate needs [23]. Alternatively, an automatic irrigation system with sensors can be used to trigger only when the environmental conditions change [24].

4. Conclusions

Most recent developments on green roofs are centered on extensive solutions, either modular or continuous, using resistant and adapted vegetation, which can come already grown in mats, having low irrigation and low maintenance needs.

Intensive green roofs enable the creation of vegetated surfaces in roofs with a wider variety of plant species. However, they are usually expensive, requiring periodical maintenance and high irrigation levels. It must be also taken into account the building load capacity, and consider that it will require structural reinforcement to support an intensive green roof, which can represent a significant additional cost to the construction of a building.

Simpler solutions as extensive continuous green roofs are more cost-effective, but have limitations in plants diversity. Recent solutions for extensive continuous green roofs include pre-grown mats of *Sedum* attached to lightweight growing medium. However, their small thickness limits root penetration of other plant species.

The alternative to these solutions can be the application of modular green roof systems. Modular systems are still relatively new [7]. They enable the installation and removal of each module individually. This can be beneficial, considering that it allows the integration of different plant species to create vegetated surfaces and also simplifies the system maintenance.

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Chapter 3

Green wall systems: A review of their characteristics

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Green wall systems: A review of their characteristics

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ABSTRACT

Current systems for greening the buildings envelope are not just surfaces covered with vegetation. Greening systems, as green roofs and green walls, are frequently used as an aesthetical feature in buildings. However, the current technology involved in these systems can maximize the functional benefits of plants to buildings performance and make part of a sustainable strategy of urban rehabilitation and buildings retrofitting.

During the last decades several researches were conducted proving that green walls can contribute to enhance and restore the urban environment and improve buildings performance.

The aim of this paper is to review all types of green wall systems in order to identify and systematize their main characteristics and technologies involved. So, it is important to understand the main differences between systems in terms of composition and construction methods.

Most recent developments in green walls are mainly focused in systems design in order to achieve more efficient technical solutions and a better performance in all building phases. Yet, green wall systems must evolve to become more sustainable solutions. In fact, continuing to evaluate the contribution of recent green wall systems to improve buildings performance and comparing the environmental impact of these systems with other construction solutions can lead to an increase of their application in buildings and therefore result in a reduction on these systems cost.

The decision of which green wall system is more appropriate to a certain project must depend not only on the construction and climatic restrictions but also on the environmental impact of its components and associated costs during its entire lifecycle.

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1. Introduction

Current systems for greening the buildings envelope are not just surfaces covered with vegetation. There are several greening systems in the market, like green roofs and green walls, which technology involved is being developed to increase their performance and longevity.

Greening systems, as green roofs and green walls, are frequently used as an aesthetical feature in buildings. However, the current technology involved in these systems can maximize the functional benefits of plants to buildings performance [1]. Greening systems can also make part of a sustainable strategy [2–4] of urban rehabilitation and building retrofitting [5–7].

At a city scale, green roofs and green walls contribute to the insertion of vegetation in the urban context without occupying any space at street level [8]. In fact, covering buildings with vegetation, when applied in a significant urban scale, can improve the urban environment by contributing to urban biodiversity [1,9], stormwater management [10], air quality [11–13], temperature reduction [14] and mitigation of the heat island effect [15,16]. At the same time, the application of greening systems can have, besides the environmental aspects, social and economic benefits. These systems encourage the fruition of urban areas [17], have a therapeutic effect by inducing a psychological wellbeing through the presence of vegetation, improve cities image [7], increase property value [18] and function as a complementary thermal [19] and acoustic protection [20,21].

Green walls have a greater potential than green roofs considering that in urban centers the extent of facade greening can be double the ground footprint of buildings [22].

At a building scale, green wall systems can be used as a passive design solution [23] contributing to buildings sustainability performance [24]. Vegetation has the potential to improve the microclimate both in winter [25], functioning as a complementary insulation layer, and in summer [26], providing shade [27–29] and an evaporative cooling effect [30]. Vegetation absorbs large amounts of solar radiation [31] while the effect of evapotranspiration of plants can further reduce the impact of solar radiation, showing increased humidity levels and surface temperatures lower than hard surfaces [32,33]. Recent studies show that green wall systems have the ability to control heat gains and losses, contributing to improve indoor thermal comfort and reduce energy demands for heating or cooling [15,34–36].

Green wall is the common term to refer to all forms of vegetated wall surfaces. Traditional green wall methods are historically known, since the Hanging Gardens of Babylon and the Roman and Greek Empires. In Mediterranean climates, vines were commonly used to cover pergolas, shading the building envelope, or on building walls, cooling the envelope during summer [37]. Since the seventeenth and eighteenth centuries, mostly in UK and Central Europe, the use of climbing plants to cover building walls proliferated [38]. In the 19th century woody climbers were commonly used as ornamental elements of buildings envelope in European and North American cities [39].

First investigations on green facades were based on botanical aspects [22]. However, since the 1980s a new idea occurred of green facades as contributors to cities ecological enhancement. The garden city movement from the end of the 19th century marked the integration of greening in urban planning. The German Jugendstil movement (Art Nouveau) from the early 20th century encouraged the integration of the house with the garden. During this period emerged some incentive programs for the installation of green facades. In fact, Berlin is an important example, from 1983 to 1997, where around 245.584 square meters of green facades were installed [22].

This paper aims to review the main green wall systems available, systematizing their main characteristics and technology involved. A search of green walls, available internationally on the market or in invention databases (e.g., Esp@cenet, Free Patents Online, Fresh Patents, Google Patents, Lusopat, Wipo – Patentscope), allowed the identification and characterization of most of the existing green wall systems. It must be noticed that this is a field in constant actualization. However, the analyzed solutions constitute a representative universe to identify the main features of green walls in terms of configuration, composition and materials used.

This paper is divided in two main sections. First, a classification of green wall systems, including a definition for different systems according to their characteristics is proposed. Second, the main requirements of different green wall systems in terms of composition, processes of installation and maintenance and their environmental impact and cost are systematized.

In order to compare the several green wall systems and their features, an analysis of their composition is made according to the following items: supporting elements, growing media, vegetation, drainage and irrigation. Additionally, given the importance of these subjects, two subsections were added to focus, first on the different phases of the systems lifecycle, namely on the differences on their installation and maintenance, and second on the environmental performance and cost of green wall systems.

2. Classification and definition

Considering the recent developments in green walls technology it is important to identify and classify all existing green wall systems, according to their construction techniques and main characteristics.

Authors use several nomenclatures when referring to all types of green wall systems. Some use the term "vertical garden" [40,41] others call them "vertical greening systems" [42], "green vertical systems" [23] or "vertical greenery systems (VGSs)" [43]. When referring to direct or indirect green facades, Ottelé et al. and Perini et al. [44,45] used the terms direct greening systems and indirect greening systems, respectively.

Another concept called "Biowalls" was mentioned by Francis et al. regarding the application of green walls in indoor spaces in order to enhance the environment [9].

This concept includes the technology involved in living walls; therefore it can be inserted in this category.

In fact, the concept of green walls refers to all systems which enable greening a vertical surface (e.g., facades, walls, blind walls, partition walls, etc.) with a selection of plant species, including all the solutions with the purpose of growing plants on, up or within the wall of a building [38]. In this paper a classification of green walls according to the different existing systems and their construction characteristics is proposed (see Fig. 1).

Green walls can be subdivided in two main systems: green facades and living walls [22,39]. There is an evident distinction between green facades, where usually climbing plants grow along the wall covering it, and the most recent concepts of living walls, which include materials and technology to support a wider variety of plants, creating a uniform growth along the surface.

2.1. Green facades

Green facades are based on the application of climbing or hanging plants along the wall. Plants can grow upwards the vertical surface, like traditional examples, or grow downward the vertical surface, in case they are hanged at a certain height [39].

Green facades can be classified as direct or indirect. Direct green facades are the ones in which plants are attached directly to

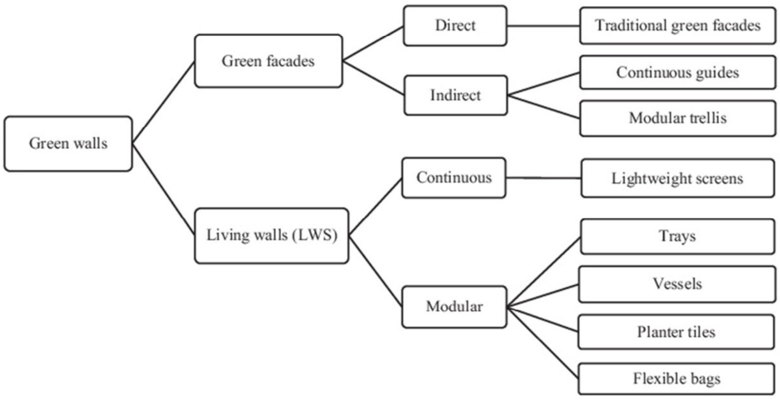

Fig. 1. Classification of green walls, according to their construction characteristics.

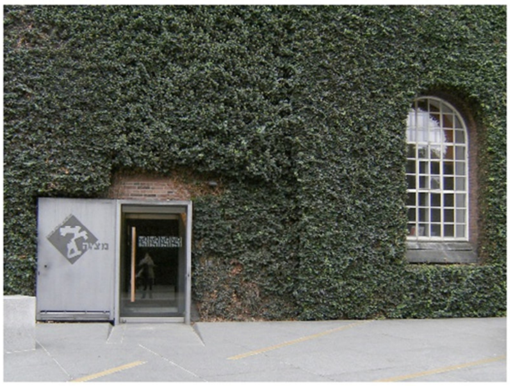

Fig. 2. Direct green facade, private house, Golegã, Portugal.

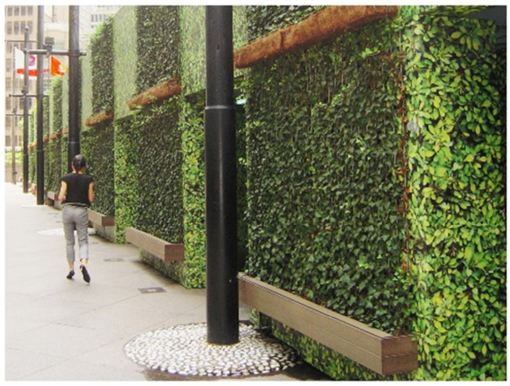

Fig. 3. Indirect green facade.

the wall. Indirect green facades include a supporting structure for vegetation.

Traditional green facades are considered a direct greening system, consisting on using self-clinging climbers, rooted directly in the ground (see Fig. 2).

New solutions of green facades are usually indirect greening systems, which include a vertical support structure for climbing plants development. In these examples plants can be rooted directly in the ground or in planters, and be guided to develop along the support structure.

Indirect greening systems include continuous and modular solutions. Continuous guides are based on a single support structure that directs the development of plants along the entire surface (see Fig. 3). Green facades with modular trellises are similar solutions, but result from the installation of several modular elements along the surface. The main differences are that modular trellises have vessels for plants rooting and an individual support structure for guiding plants development [46].

Fig. 4. Continuous living wall system, Caixa Forum, Madrid, June 2013.

2.2. Living walls

Living walls are a quite recent area of innovation in the field of wall cladding. They emerged to allow the integration of green walls in high buildings. Living walls allow a rapid coverage of large surfaces and a more uniform growth along the vertical surface, reaching higher areas and adapting to all kinds of buildings. They also allow the integration of a wider variety of plant species.

Living wall systems (LWS) can be classified as continuous or modular, according to their application method. Continuous LWS are based on the application of lightweight and permeable screens in which plants are inserted individually [47,48]. Modular LWS are elements with a specific dimension, which include the growing

Fig. 5. Modular living wall system, Natura Towers, Lisbon, August 2012.

media where plants can grow. Each element is supported by a complementary structure or fixed directly on the vertical surface.

Continuous LWS are also known as Vertical Gardens, a name given by the French botanist Patrick Blanc who reported his first "Vertical Garden", also designated as "Mur Vegetal" in 1994. Patrick Blanc spread the application of this type of LWS all around the world. His work is included in several buildings of the most famous architects (see Fig. 4).

In the category of living wall systems, the alternative to vertical gardens is the application of modular living wall systems (see Fig. 5), which is relatively new [39]. Modular LWS have differences in their composition, weight and assembly. They can be in the form of trays, vessels, planter tiles or flexible bags.

Trays are usually rigid containers, attachable to each other, that can hold the plants and substrate weight.

Vessels are an adaptation of the most common support for plants with the difference that they can be fastened to a vertical structure or be attached vertically to each other.

Planter tiles highlight the modular elements shape as elements of design for building's exterior or interior cladding. More than the creation of vegetation layer, they function as a modular cladding with insertions for plants.

Flexible bags include a growing media and lightweight materials that allow the application of vegetation in surfaces with different forms, as curved or sloped surfaces.

3. Systems requirements

Most recent developments in green walls are mainly focused in systems design and their elements (supporting elements, growing media, vegetation, irrigation and drainage) in order to achieve more efficient technical solutions and a better performance in all building phases (installation, maintenance and replacement).

The adaptability to more building types (e.g., commercial spaces, high rise buildings), construction methods (new or existing building walls) and types of surfaces (e.g., sloping surfaces, indoor partition walls and free-standing structures) [49,50] is also the concern in the evolution of green wall systems.

3.1. Supporting elements

Traditional or direct green facades usually have no support structure. They rely on the capacity of climbing plants to attach themselves to the vertical surface. However, when the vegetation fulfils full coverage can become too heavy and the risk of falling is increased.

Indirect green facades function as "double-skin facades", creating an air gap between the building surface and vegetation. The application of a support structure avoids vegetation to fall. These systems, either modular or continuous, anchor and hold the vegetation weight, contributing to increase the system resistance to environmental actions (e.g., wind, rain, snow). Most support structures for indirect green facades include continuous or modular guides, as cables, wires or trellis made of galvanized or stainless steel [51,52]. Steel structures and tensile cables (see Fig. 6) can be used to hold climbing plants with denser foliage and to support their weight. Grids and wire-nets have smaller intervals and can be used for slow growing plants support [53]. Some indirect green facades systems, mostly modular trellises, include pots filled with substrate and individual support structures, allowing the suspension of the elements along the wall at various heights. New forms of modular trellises include a curved grid to give the facade rhythm and three-dimensionality to the wall [51,52].

Living walls usually include a frame to hold the elements and a support for plants.

Continuous LWS are based on the installation of a frame fixed to the wall, forming a void space between the system and the surface. This frame holds the base panel and protects the wall from humidity. The base panel supports the next layers. It is covered with layers of permeable, flexible and root proof screens, stapled to the base. The external layer of screen is then cut to form pockets [47,48] for the introduction of plants individually (see Fig. 7).

Modular LWS can take several forms (e.g., trays, vessels, planter tiles or flexible bags) requiring a different structure.

Modular trays are usually composed of several interlocked parts, made of lightweight materials as plastic (e.g., polypropylene or polyethylene) or metal sheets (e.g., aluminum, galvanized steel or stainless steel) [54–59].To ensure the system continuity, each module normally includes an interlocking system on the sides to connect to each other. These modular elements may also contain a front cover forming a grid to prevent plants to fall (see Fig. 8).

Trays and vessels are usually fixed to a vertical and/or horizontal frame attached to the surface. The back surface can include hooks or mounting brackets [56,58] for their suspension in the frame profiles connected to the vertical surface.

Modular vessels allow the installation of several plants in each element along the same row. They are commonly made with polymeric materials and due to their form have a significant visual impact on the building surface.

Fig. 6. Continuous green facade.

Fig. 7. Continuous living wall system.

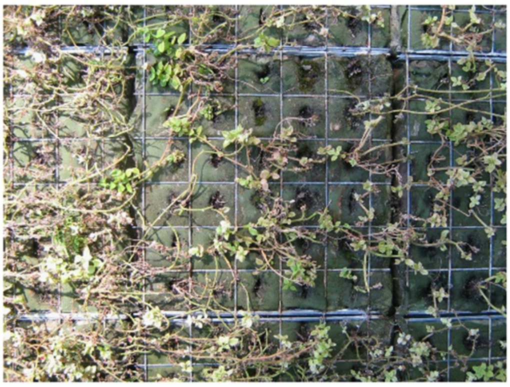

Fig. 8. Modular living wall system.

Planter tiles are connected to each other by juxtaposition. They often include a flat back fixed to the building surface and an area in which the plants are inserted individually. These solutions can be built in lightweight or porous materials like plastic or ceramics [60]. Depending on the system, tiles can be glued to the vertical surface [61] or be fixed with mechanical fastening [60].

Modular LWS can also take the form of elongate bags, filled with growing media, made of flexible polymeric materials which are cut to insert each plant [62].

3.2. Growing media

In the context of green facades only modular systems require the selection of a growing media, which must be lightweight, considering that each element will be suspended, and adapted to the selected plant species and environmental conditions.

In the field of living walls, continuous LWS also do not have substrate. As mentioned before, these systems use lightweight absorbent screens where plants are inserted in pockets. Continuous LWS are commonly based on a hydroponic method, requiring a permanent supply of water and nutrients due to the lack of substrate. Hydroponic systems allow the growth of plants without soil, using screens constantly moist by the irrigation system. The lack of soil is compensated by providing the necessary nutrients for plants development through irrigation water.

Modular LWS are commonly filled with a growing media where roots can proliferate, made of organic and inorganic compounds [49,58,59] or include a layer of inorganic substrate, usually foam, to reduce its weight. Most modular LWS include a growing media based on a mixture of light substrate with a granular material, expanded or porous (e.g., mineral granules with medium to fine particles, coconut fibbers or recycled fabric) in order to obtain a good water retention capacity [56,63]. The substrate may be improved with nutrients for plants growth (e.g., mixture of organic and inorganic fertilizers, metal chelates, minerals, nutrients and hormones for plants or other additives) [58]. Some modular LWS indicate the insertion of growing media into geotextile bags to prevent its detachment. These bags can occupy the entire module and allow the insertion of several plants [56], or cover the growing media of each plant individually [54,57]. Alternatively, each plant can include an individual front cover to avoid the growing media to fall [58].

3.3. Vegetation

The appropriate vegetation depends on climatic conditions, the building characteristics and the surrounding conditions, in which the green wall is inserted. The analyzed systems show some concerns with vegetation longevity.

Climbing plants are considered a cheap solution of vertical greening. These plant species can contain two main types of foliage, evergreen or deciduous. Evergreen plants maintain their leaves all year and deciduous plants lose their leaves during the fall, having a strong visual change along the year.

Climbing plants can be self-supporting, attaching themselves to the vertical surface (e.g., root climbers and adhesive-suckers) or be supported by a structure [52] were they can hold (e.g., twining vines, leaf–stem climbers, leaf climbers and scrambling plants). They were traditionally used in Germany and France to cover the exterior walls of small buildings. In warm-summer climates vines were commonly installed in pergolas to shade buildings envelope [39]. It is also important to consider that climbing plants have growing limitations. Some species achieve 5 or 6 m, others 10 m and some 25 m high [39] and take about 3–5 years to achieve full coverage [53].

A study performed in the Mediterranean Continental climate compared the development of several climbing plants, perennials (*Hereda helix, Lonicera japonica*) and deciduous (*Parthenocissus quinquefolia, Clematis sp*), according to the achieved foliage density after one year of development. It revealed that *Parthenocissus quinquefolia*, also known as Virginia creeper, provided greater density of foliage, but none of the selected species could cover the entire surface after one year. Some species also reveal difficulties to adapt to the climatic conditions, with high temperature variations along the year and low rainfall, as *Clematis* which was affected by summer conditions [30].

Living wall systems allow the development of new aesthetical concepts of green walls, based on the creation of artistic solutions with plant species, exploring the use of patterns, variations in color, texture, foliage forms and density, vitality and growth. These solutions brought a wider variety of plant species to green walls, allowing the integration of shrubs, grasses and several perennials as long as their watering and nutrient needs are taken into account.

Hydroponic systems make possible the growth of a wider variety of plants, in different states of development: grown plants, cuttings or seeds [64]. In these cases vegetation is selected according to the desired aesthetic effect [56,65], requiring the appropriate irrigation and nutrients for an adequate plant development. Therefore, it is important to analyze plants development, color, blooming, foliage and the global plant composition, according to the artistic intentions to a certain building (e.g., building framing in the urban context, advertisement of a particular company, or marking distinction of an certain building or interior space).

However, in order to fulfill sustainability goals, vegetation must have low irrigation needs (e.g., use of native plants), be adapted to local conditions of exposure (e.g., sun, semi-shade or shade) and weather conditions (e.g., wind, rainfall, heat, drought and frost).

Recent examples of modular LWS include the option of using *succulent* carpets in green walls instead of perennials and shrubs. The use of drought tolerant plant species as succulents [1] reduces the needs of irrigation. These plant species have also low maintenance and contribute to the minimization of the system weight. However, succulent carpets acquire the appearance of a flat vegetated surface, which can be interesting in small walls. In larger surfaces the use of perennials and shrubs allows the creation of more ornamented landscapes due to the variety of colors and textures that these plants can include. A Japanese system [62] also exemplifies the application of certain shrubs which can be used in inclined surfaces (e.g., *Juniperus chinensis*, *Juniperus conferta*, *Euonymus Fortunei*, *Cotoneaster*, *Cotoneaster Horizontal*, *Vitex rotundifolia*).

Green walls have a particular potential for urban agriculture, particularly in cities where there is lack of land for cultivation, reducing the environmental impact related to food production and distribution [53]. New concepts of green walls consider the integration of vegetables and aromatic herbs in green facades, continuous LWS [48] or modular LWS (Fig. 9), as planters [60] or vessels [61], increasing the functional potential of the system itself to building users.

3.4. Drainage

Excess fluid drainage in green walls takes place by gravity.

Continuous and modular LWS use geotextiles that encourage drainage along the permeable membrane while preventing roots proliferation.

Modular trays take advantage of the overlap of modules and materials to improve drainage and water excess reuse to the modules below. For a better drainage the bottom of a modular systems can be concave, inclined, perforated or be made in a porous or absorbent material [55]. Other examples as vessels mention the use of a filter material applied at the bottom of the module [61] (e.g., inoculated sand or other mean to purify rainwater, remove toxins and heavy metals) or a granular inert filler [65] (e.g., expanded clay, expanded slate, gravel) which promotes the drainage and development of roots. Some examples of modular systems also mention the insertion of grooves or holes on the sides and back face of modules, for a better aeration and removal of excess moisture contained in the substrate [56,59].

Fig. 9. Modular living wall with edible plants [66].

3.5. Irrigation

The irrigation needs depend on the type of system, plants used and climatic conditions.

Modular green facades and LWS require an irrigation system in order to provide the necessary water to plants development. The irrigation water can be enriched with nutrients, fertilizers, minerals, phosphates, amino acids or hydroponic materials to improve the vegetation development and vivacity.

The water supply of LWS is made through the installation of a continuous irrigation tube located at the top. Continuous LWS have an irrigation system installed at the structure top connected to the central irrigation system. In the case of continuous LWS the permeable screen allows the uniform distribution of water and nutrients along the surface.

Some modular LWS in the form of trays include a recess in the top face of the module to insert the irrigation tube. The trays include several holes in the recess for watering the growing media by gravity [54,55,57,58]. Drainage holes located in trays bottom are used to allow excess water to irrigate the modules underneath.

The irrigation tubes and connectors can be produced in several materials (e.g., rubber, plastics, piping thermoplastic, silicone and irrigation hose) containing different outputs (e.g., drip, sprinkler, holes, pipe) with distribution and intensity adapted to the plants irrigation needs. The irrigation system can also include a filtration system to prevent clogging.

Some LWS also mention strategies for minimizing the consumption of treated water. There are strategies like rainwater recovery [56] from the building roofs, reuse of the fluid collected in the drainage system [67] and monitoring water supply needs [55], through the installation of sensors [47,48] that control the collecting water tank level, the irrigation time and weather conditions (e.g., quantity of rainfall, humidity, temperature, atmospheric pressure).

Other LWS, either modular [60,68] or continuous [47,48], also refer the installation of a gutter in the system base, recovering excess water storing it and reintroducing it into the irrigation system.

Another strategy consists in the application of sensors in the growing media for nutrients needs quantification. This can be important to minimize nutrients consumption and match the plants needs.

3.6. Installation and maintenance

Green facades, including climbing species, are more cost-effective during the installation process but have limitations in plants diversity. When there is the necessity of plants replacement, these systems show difficulties in ensuring vegetation continuity. During plants growth, some climbing plants also require guidance to ensure that they cover the entire surface. It is also important to refer that some climbing plants can damage buildings surface, destroying it with their roots and entering in voids or cracks.

Modular trellises have advantages when compared to continuous guides on the installation and maintenance processes. The installation of plants at several heights decreases significantly the impact of the disperse growth of climbing plants along the surface and enables the substitution of unsuccessful plants.

A crescent number of modular LWS emerge in the market to minimize installation, maintenance and replacement problems.

Some modular systems enable to disassemble each module individually [59] or include a removable front cover [57] for wall maintenance or vegetation replacement. Some modular elements can also be nested into each other in order to simplify the transportation and application processes.

When comparing continuous LWS to modular LWS, continuous LWS enable the creation of vegetated surfaces with a wider variety of plant species, and can be lighter, has a density of around thirty plants per square meter and less than 30 kg/m^2 [64]. However, continuous LWS are commonly hydroponic systems, requiring a permanent supply of water and nutrients, which constitute a sustainability disadvantage and result in higher maintenance costs due to higher irrigation needs.

In fact each green wall system has its own characteristics, with advantages and disadvantages depending on their aesthetic potential, cost and maintenance needs (Table 1). The selection of the most adequate system is directly related to the building characteristics (e.g., orientation, accessibility, height) and climatic conditions (e.g., sun, shade and wind exposure, rainfall). This is why it is important to understand their differences in composition and their main characteristics (Table 2).

3.7. Environmental performance and costs

To better understand if green wall systems may be considered sustainable solutions, several studies were conducted by researchers to compare the environmental performance of different green walls systems during their entire lifecycle.

Direct green facades are a more sustainable [69] and economic solution [45]. These systems have a small environmental burden considering that they have no materials involved and have low maintenance needs.

When analyzing the life cycle of some LWS their sustainability may be questioned. Differences in the type of materials used, their durability, recycling potential, vegetation durability and water consumption can have a significant impact on the total environmental burden [44,70]. As shown by Ottelé et al. the integration of stainless steel as supporting system can have an impact 10 times higher than using other recycled materials (e.g., HDPE, hard wood with FSC certificate or coated steel) [44]. Another important matter is materials durability. Several materials as PVC and others have a limited durability requiring its replacement more than once during buildings life expectancy.

Nevertheless, green wall systems frequently use materials with high environmental impact. Recent studies proof that some systems can have a reduced environmental burden by contributing to the thermal resistance of the wall, leading to a reduction on energy demand for heating and cooling [44].

The cost of green wall systems can also be a variable with significant impact on the selection process. LWS are more expensive when compared to direct and indirect green facades. Direct and indirect green facades can cost less than 75 €/m^2 [45].

Table 1
Comparison of green wall systems advantages and disadvantages.

System	Category	Sub-category	Advantages	Disadvantages
Green facades	Direct greening	Traditional green facades	No materials involved (support, growing media, irrigation) [71] Low environmental burden [44] Low cost [45]	Limited plant selection/climate adaptability Spontaneous vegetation development [45] Slow surface coverage [53] Scattered growth along the surface [23] Surface deterioration [23,39]/plants detachment Maintenance problems [33,45]
	Indirect greening	Continuous guides	Vegetation development guidance [53] Low water consumption [71]	Limited plant selection/climate adaptability [30,71] Slow surface coverage [53] Scattered growth along the surface [23,26] High environmental burden of some materials [44,71]
		Modular trellis	Lightweight support [23] Vegetation development guidance [51] Controlled irrigation/drainage [51] Easiness to assemble and disassemble for maintenance [30] Plants replacement	Limited plant selection/climate adaptability [46] High environmental burden of some materials High installation cost [45]
Living walls	Continuous systems	Felt pockets vertical gardens	Uniform growth [71] Flexible and lightweight [47,48] Increased variety of plants/aesthetic potential [45,64,71] Uniform water and nutrients distribution [48]	Complex implementation [23] High water and nutrients consumption [71] Frequent maintenance [44] Limited space for root development [48] High installation cost [45]
	Modular systems	Trays	Easily disassembled for maintenance [57,59] Increased variety of plants/aesthetic potential [45,64,71] Controlled irrigation/drainage [55,67]	Complex implementation [23] Heavier solutions Surface forms limited to trays dimensions High environmental burden of some materials [44,71] High installation cost [45]
		Planter tiles	Increased variety of plants/aesthetic potential [45] Attractive design of modules [60]	Complex implementation [23] Limited space for root development [60] Surface forms limited to tiles dimensions [60] High installation cost
		Flexible bags	Adaptable to sloped surfaces [62] Increased variety of plants/aesthetic potential [45]	Complex implementation [23] Heavier solutions due to growing media/limited to buildings maximum load [62] High installation cost

Table 2
Summary of green wall systems composition.

System requirements	Green facades	Continuous LWS	Modular LWS
Support	Cables, ropes, nets, trellis in stainless steel, galvanized steel, wood, plastic, glass fiber [51–53,67]	Geotextile felts [47,48,64]	Galvanized steel, stainless steel, lightweight and/or flexible polymers, ceramics [54–62]
Growing media	Ground soil or vessels filled with substrate [39,51]	–	Substrate mixture including organic and/or inorganic compounds [45,47,48,56,58,63,64]
Vegetation	Climbing plants (evergreen or deciduous) [24,30,33,39,42,45,52]	Shrubs, grasses and perennials [6,64]	Shrubs, grasses, perennials and succulent plants [6,31,45]
Drainage	Vessels with inferior holes [51]	–	Lateral and inferior holes [54–59,63]
Irrigation	Drip line inside vessels [51,60]	Drip line on the top of the wall [47,48,64]	Drip line on top of each module [54–59,63]

Modular green facades have variable costs depending on the materials used, for example a system using galvanized steel can be 4–8 times more expensive than a system using HDPE. In the case of LWS the costs are also very dependent on the materials used and the system complexity, reaching to a cost of 1200 €/m^2 [45]. Indeed the cost depends also on the application process (considering the surface dimension and accessibility) and maintenance needs (e.g., irrigation, nutrients, plants replacement).

Nevertheless, improving the performance evaluation of recent green wall systems can lead to an increase of their application in buildings and therefore result in a reduction on their cost.

Importantly, the decision of which green wall system is more appropriate to a certain project must depend not only on the construction and climatic restrictions but also on the environmental impact of its components (e.g., energy or water used and materials recyclability) and associated costs during its entire lifecycle.

4. Conclusions

The analysis of the most relevant systems in the field of green wall systems demonstrates that there is a significant evolution in this field. Some examples either modular or continuous focus on its lightness, through the application of geotextile and polymeric materials. This can be very useful with regard to the application of these systems in buildings rehabilitation [71].

Continuous solutions are often lighter than modular systems. But most recent developments of green wall systems design are mostly focused on modular systems, offering advantages of installation, allowing a rapid coverage of the entire surface, and simplifying their maintenance, enabling the disassembly and replacement of each element.

In the field of green wall characteristics, the main concerns are to find new strategies for a better performance and durability through the integration of water retention materials, drainage means and simpler assembly and maintenance processes.

Systems adaptability is still a field of development. New solutions must focus not only in the application in new buildings but also in the rehabilitation of existing buildings, introducing greening in historical areas [17]. Most systems are designed to be applied in the vertical plan, allowing, in some cases, their application in inclined plans with some restrictions. Therefore, green walls must evolve and adapt to different surface forms and inclinations (e.g., curved, vertical or horizontal surfaces), with the convenient adaptations [72].

Considering the analysis of different types of green wall systems, it can be understood that innovation is mostly centered in the improvement of their design to achieve a better performance, during the installation, usage or maintenance processes [73].

Yet, green walls must evolve to become more sustainable solutions [74], through the use of materials with less incorporated energy and CO_2 emissions and the application of climate adapted plant species with less irrigation needs [73]. Some examples already show sustainability concerns by using natural or recycled materials and native plants, integrating water recovery systems and sensors for water and nutrients minimization.

In fact, continuing to evaluate the contribution of recent green wall systems to improve buildings performance and comparing the environmental impact of these systems with other construction solutions can lead to an increase of their application in buildings and therefore result in a reduction on these systems cost.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.07.203.

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Chapter 4

Modular system design

1. Introduction

The knowledge obtained from the study of the various green roofs and green wall systems, the analysis of their characteristics, construction techniques and materials used is fundamental for the design of a new system. Considering the bibliographical research carried out, it is verified that the majority of the analysed systems focus on lighter and thinner systems that are easy to apply and provide immediate plant coverage. Also, the design trend of these vegetated systems is the use of modular systems, quick and simple to install and allowing the surface maintenance. However, the integration of sustainability principles in the design of green roofs and green wall systems is a subject not fully addressed.

Also, most solutions are focused on solving one constructive solution, with no solutions that contribute as a green roof and a green wall simultaneously. It is therefore intended to exploit this polyvalence by considering the specificities of each surface, taking into account the selected materials and the functional requirements of the system when applicable on horizontal, vertical or sloped surfaces.

This study consists in promoting materials reuse through the development of a high value product from waste materials. The aim is to provide unique properties to the system and create a more sustainable solution than the conventional extensive green roofs and modular living wall systems. This study presents the development of the Geogreen system design, based the analysis of its configuration and composition.

2. Design concept

The design concept of a modular system for vegetated surfaces (Geogreen) is the main focus of this research. The intention is to create a versatile solution for green roofs and green walls.

The goals of its design are:

- Continuity and uniformity assurance of the vegetal layer;
- Simplification of the construction and maintenance processes;
- Adaptability to different supports;

- Minimization of plant irrigation;
- Minimization of its environmental impact;
- Improvement of buildings performance.

The intention of Geogreen modular system is to develop a passive cooling solution with environmentally sustainable concerns. One of the purposes is to find strategies that allow the minimization of its environmental impact, by reducing the system embodied energy and therefore the CO_2 emissions. Furthermore, this solution combines the application of local recycled materials with endemic vegetation.

2.1 Precedents

Several ideas preceded the development of a new modular system. The solutions presented below were the basis for the development of Geogreen modules conceptual form.

One of the first ideas for this module was based on squared modules (30x30cm) that allow a continuous vegetation layer (Figure 1). To improve the system continuity an interlocking system with tongue and groove fitting was inserted in the module sides. Each module included a lower layer made of expanded cork board (ICB) with thermal and acoustic insulation properties and an upper layer made of alkali-activated binder to provide resistance and retain moisture. The roofs slab which is the support for this system, should be waterproofed and include a drainage layer. The modules would be fitted over the drainage layer. At the top of the interlocked elements would be placed the vegetation and substrate with the thickness suitable for the development of the vegetation. The modules dimensions and thickness could vary to ensure an appropriate weight for handling and adequate strength of each material. The type of substrate and alkali-activated water retention capacity would have to be studied to ensure the humidity levels necessary for vegetation development and minimize irrigation needs.

After this, was developed the idea of square modules that can be applied either in roofs or walls (Figure 2). It would be formed by squared modules (30x30cm) with also tongue and groove fitting. The interlocking system would allow a better continuity of the system. Each module would have a base layer, to provide strength and retain moisture, and a top layer made of expanded cork. The top layer could include openings for plants. The size of the openings and thickness of the insulation cork board could vary, depending on plants selection.

The concept design is also based on the idea of individual plants insertion into the module and integration of an interlocking system, e.g. as a brick wall or concrete pavement (Figure 3).

The temporary installation Public Farm 1 in New York made by WORKac architects was also a source of inspiration (Figure 4). The structural material is cardboard tubes, a recyclable and biodegradable material, which is used as planters. The tubes are preassembled in a hexagon pattern around a seventh central tube which alternates as a “picking hole” to access the crops or a structural column, extending to the ground [1].

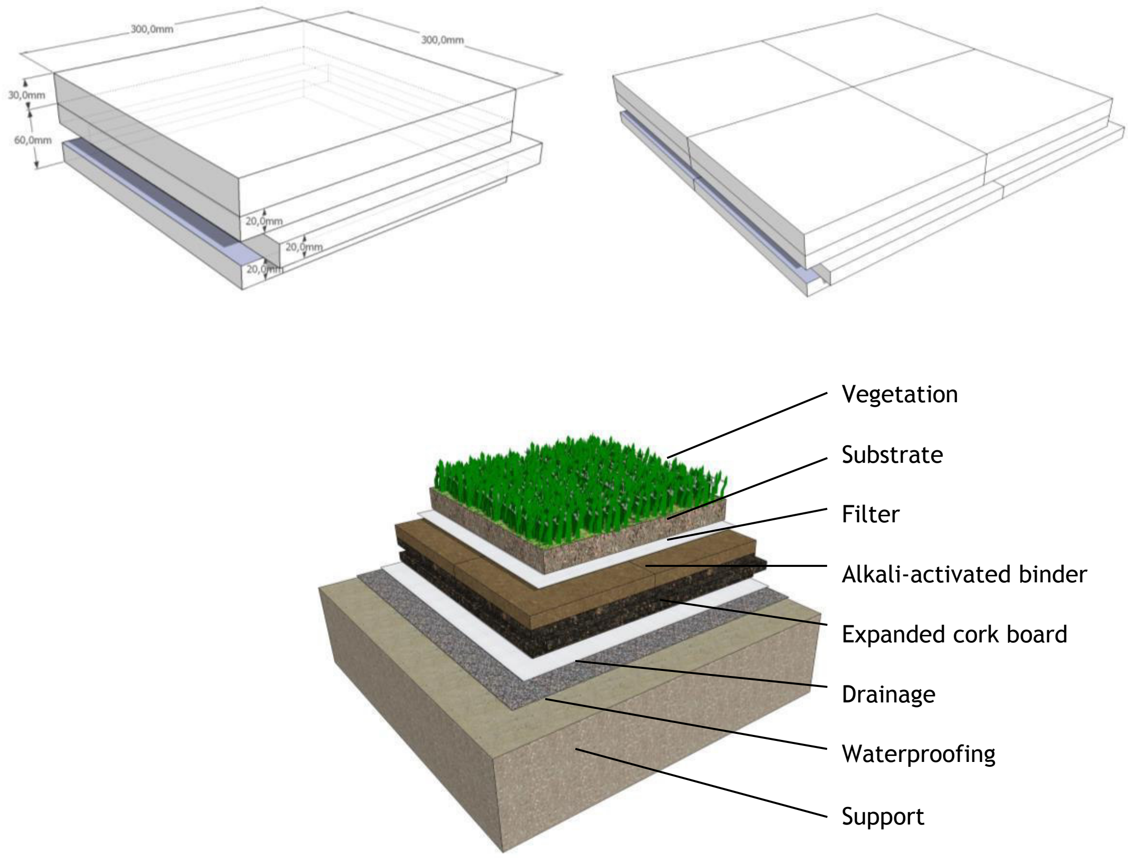

Figure 1 – Model 1, modular element for green roofs.

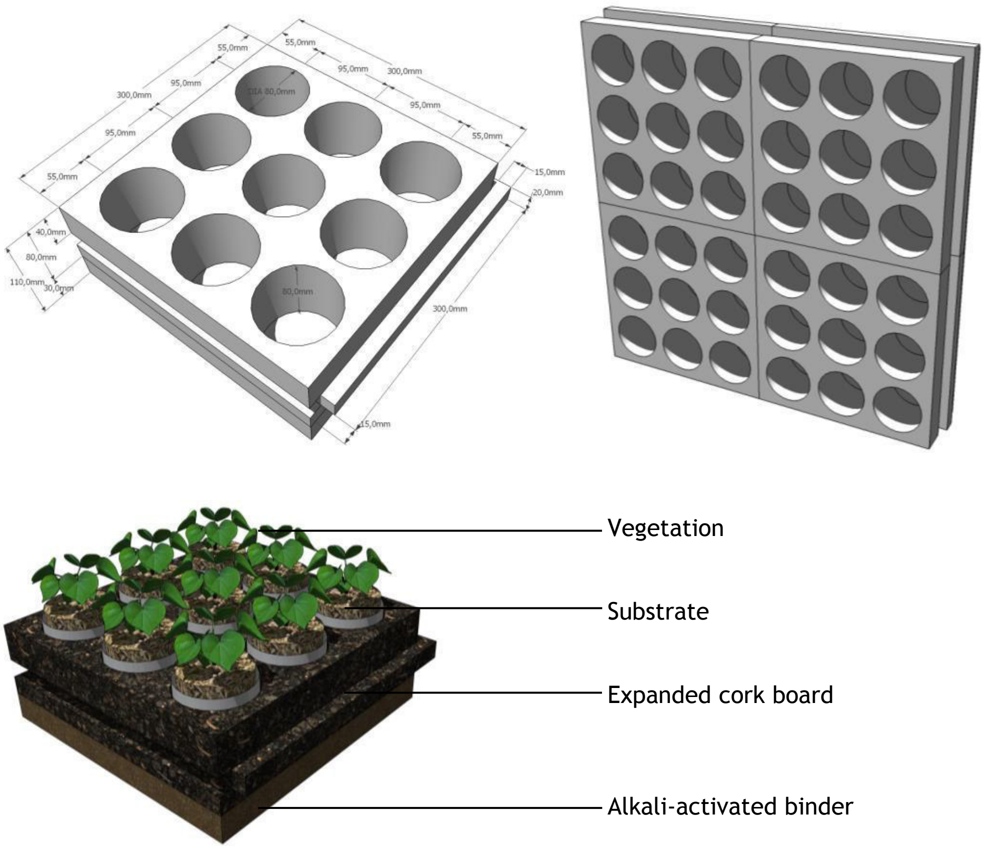

Figure 2 – Model 2, modular element for green walls and green roofs

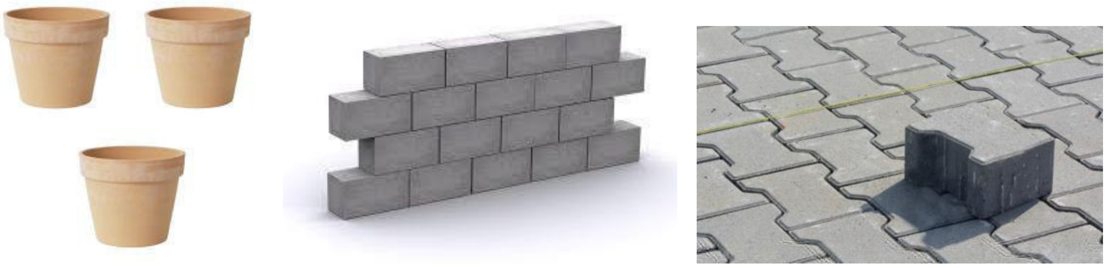

Figure 3 – Conceptual elements behind the Geogreen design

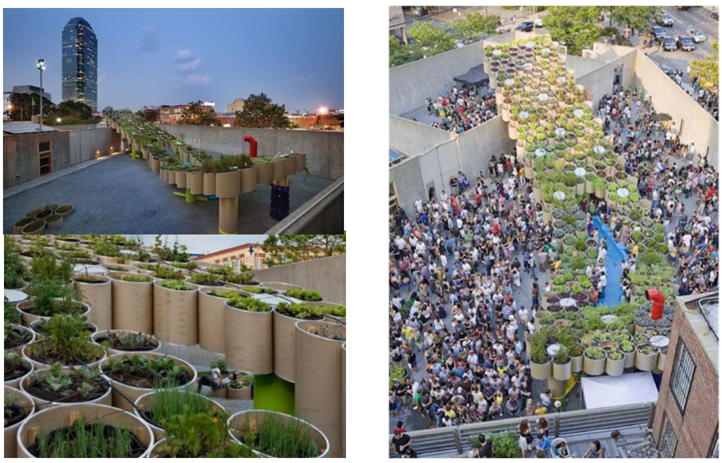

Figure 4 – Public Farm 1, by WORKac architects [1]

2.2 System Configuration

Designed to be more versatile than the most common extensive green roofs and living wall systems, the Geogreen system allows the construction of either green roofs or green walls.

The selection of materials to be integrated in the system composition was made according to their function, characteristics and specific properties of each material. The aim is to guarantee a good performance and create a more sustainable system.

The Geogreen module comprises a base made with an alkali activated binder and a top layer of expanded cork board (ICB) with opening to allow the insertion of vegetation. The top layer may be attached to the base plate by gluing or mechanical fastening.

The intention is to create vegetated surfaces based on elements of small size, allowing a manual installation without the use of mechanical equipment.

Designed to simplify the installation and maintenance processes, it allows the insertion and substitution of each module individually when in normal functioning.

The base is 2 cm rigid board made from a waste-based alkali-activated binder designed to absorb water and keep the substrate moist. The upper layer consists of a high density 80mm insulation cork board (ICB) with openings cut by CNC. Each module comprises 9 circular openings in the ICB board for substrate and plants insertion. The openings are aligned in each row and unaligned in different rows. Each module has 38,5x30x10cm (length x width x thickness) as presented in Figure 5.

The application process consists in placing the modules parallel to one another in the same row and mismatched between rows, so that they remain locked together (Figure 6). The fastening system is adaptable to different supports, allowing the application of this system either in new buildings and retrofitting.

In order for the system to be installed on vertical or horizontal surfaces the modular elements are fixed to the support using a fastening system. The choice of the most appropriate solution to support the modular elements is explained further in the subchapter Fastening System.

When the surface is fully assembled the openings are spaced equally to allow a uniform grow along the surface. Plants with substrate are then inserted individually in the module openings (Figure 7).

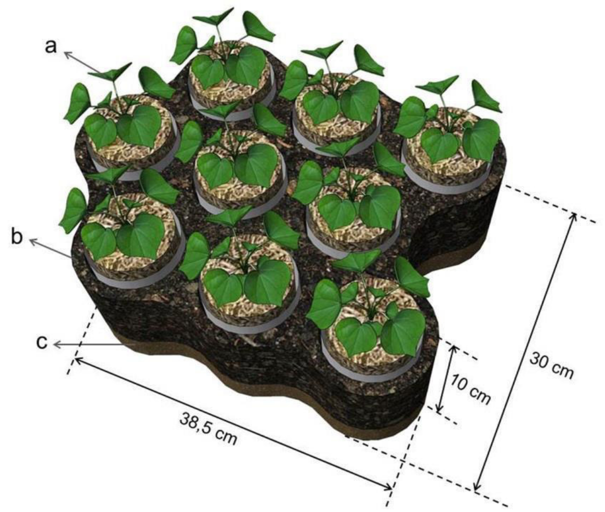

Figure 5 - Geogreen module: a. Adapted plant species inserted in low weight substrate; b. expanded cork board; c. alkali-activated board.

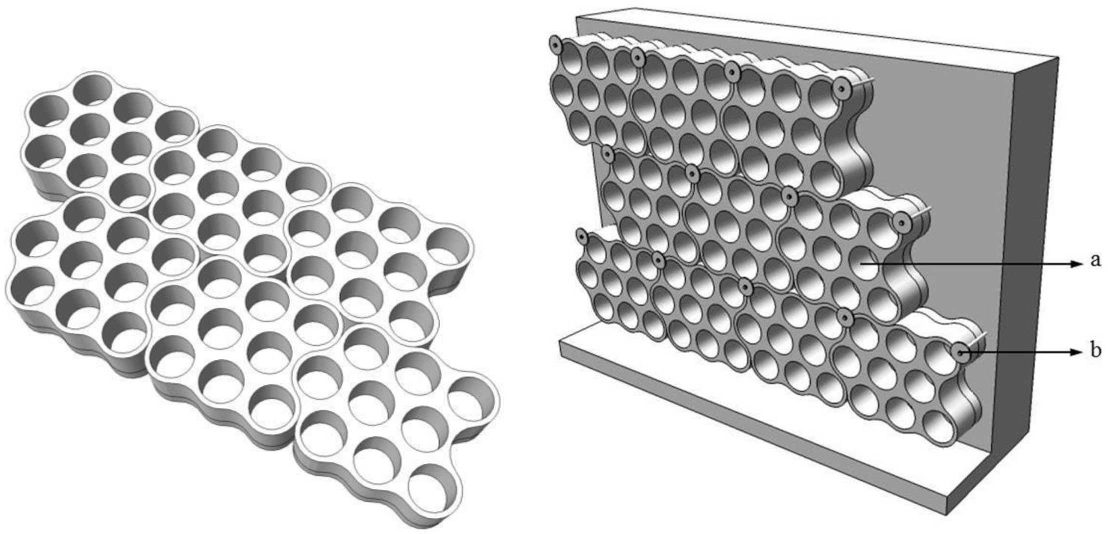

Figure 6 - Assembly in horizontal and vertical positioning: a. Geogreen modules; b. Fastening system.

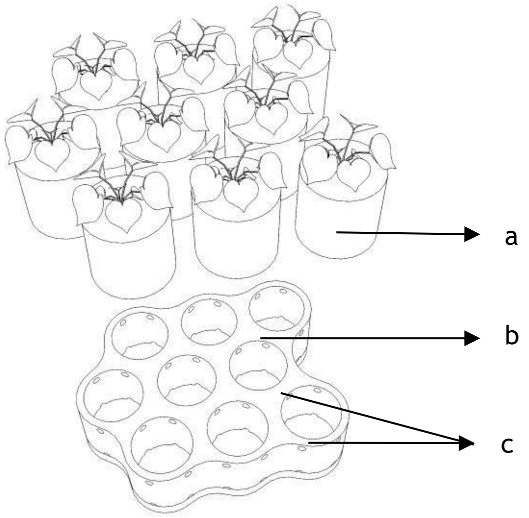

Figure 7 - Geogreen module with vegetation and substrate.
a. Vegetation and substrate; b. Geogreen module; c. Drainage holes.

Considering the ICB density to allow an adequate resistance, a new strategy was proposed to ensure the drainage of excess water contained in the substrate. For this purpose there may be holes in the side faces of the ICB. These holes were proposed near the base, to avoid roots rotting, and on top of each opening to avoid waterlogging the substrate (Figure 7). The insertion of drainage channels can be evaluated according to the positioning of the modular elements, the type of substrate and the vegetation irrigation needs.

The modular elements are versatile and can be cut and finished in the limits to align with the surface to be cladded. These elements may be covered partially to prevent water and moisture penetration. However the connections detailing must be performed according to the configuration and dimensioning of the surface. It should be executed and detailed on a case-by-case basis.

2.2.1 Alternative design

However, other configurations, dimensions or compositions are possible, provided that continuity of the system is ensured and that each element is not excessively heavy. It is important to keep the goals of manually install the system, dismantlement for maintenance purposes and use in buildings rehabilitation.

Some configuration alternatives were presented in the Patent (PT106022) of this system. These configurations show how the form of this system isn´t enclosed to a single proposal, allowing it to take other shapes and sizes (Figure 8).

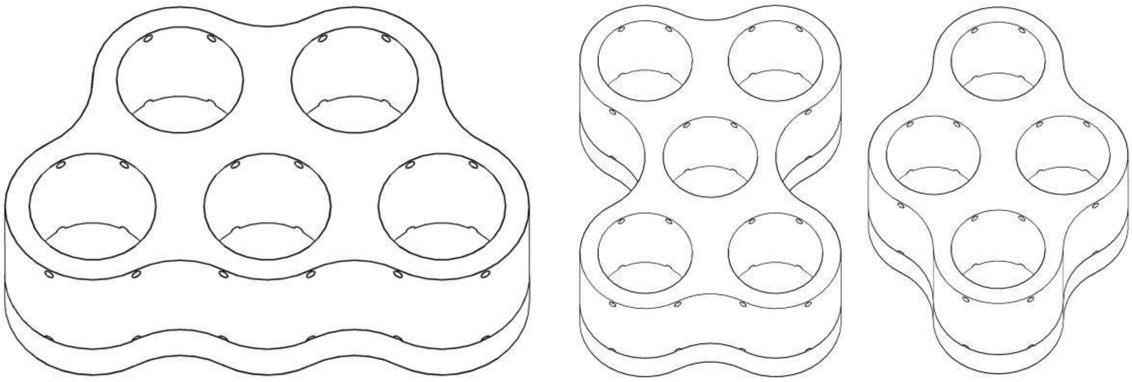

Figure 8 - Alternative configurations of Geogreen module

2.3 Elements selection

Each module comprises two main layers (Figure 9) an alkali-activated base and an upper layer made of insulation cork board with circular openings for plant insertion.

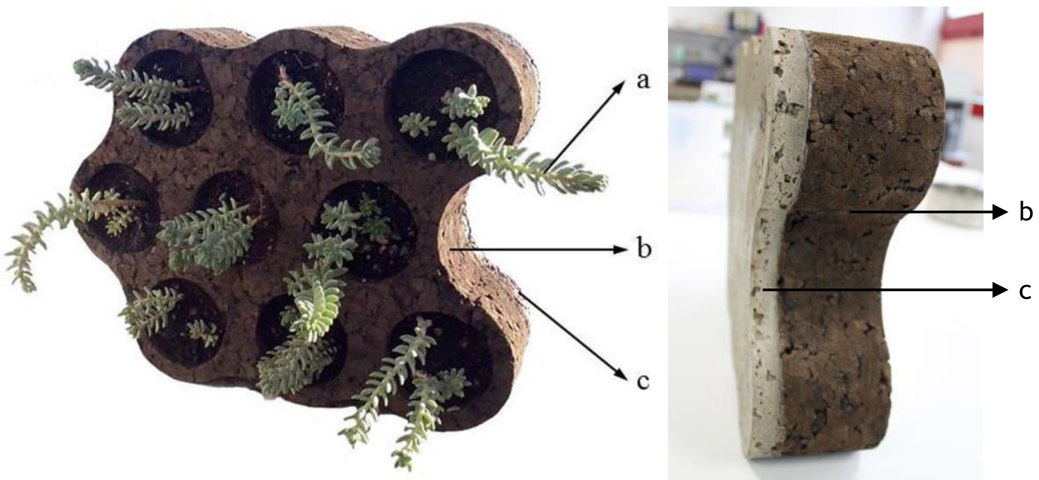

Figure 9 - Geogreen modular system design with plants and substrate.
a. Adapted plant species; b. Upper layer in expanded cork board (ICB); c. Base layer in alkali-activated binder.

2.3.1. Alkali activated base

Mine and quarrying represent 28% of total waste production in European Union [2]. So, it is becoming mandatory to find alternative applications for mine waste, promoting their recycling and reuse. Panasqueira mine in Portugal is one of the largest tungsten mines in the world. It generates several tons of waste mud and coarse aggregate every year [3].

Recent research indicates that mine waste mud from Panasqueira mine is rich in silica and alumina [4]. This waste material has been tested as a precursor to produce alkali-activated binders, as it shows good reactivity with alkaline activators like sodium silicate and sodium hydroxide [5]. Preliminary results showed that these mine waste binders presented good durability performance regarding abrasion and acid resistance, as well as a positive environmental performance in leaching tests [6]. However, the microstructure and mechanical properties of these materials depend strongly on the chemical compositions of the starting materials [7, 8, 9]. These materials reveal excellent properties, in particular on their durability, resistance to acidic attack, behaviour at high temperatures and fire resistance and resistance to frost attack [10]. Also some studies show that alkaline activation is a secure process of encapsulation of heavy metals [6, 11]. Recent studies also demonstrate that alkali-activation can be improved by mixing Panasqueira mine waste mud with other sources of silica, like sand and waste glass [12, 13, 14].

One aim of this study is to create a more sustainable solution by integrating in the modular system alkaline activated materials obtained from mine waste mud. The intention is to develop a product with added value, which can make environmentally and economically viable transforming industrial waste materials [4, 11]. Based on the reuse of industrial waste, alkali-activated materials are integrated into this modular system with the purpose of absorbing water and slowly release it to the plants, minimizing its irrigation needs.

In this context, several mixtures are tested to identify which alkali activated binder combines good mechanical strength, reduced density, increased porosity and water retention capacity to apply this material in the modular elements for vegetated surfaces. The application of non-conventional alkaline activation materials, namely their selection and determination of their properties, are based on current knowledge on alkaline activated binders of mine residues. The results obtained are presented on Chapter 6.

The alkali-activated base is prepared into a mold and sealed to cure in a ventilated oven at 60ºC for 7 days. After 48h it is removed from the mold and continue curing under the same conditions until reaching 7 days. Several prototypes were developed to achieve the best solution for this purpose (Figure 10).

After curing it must be ensured that the back side of the base plate is properly waterproofed to prevent water absorbed by the base from migrating towards the support surface. The base must be in an unventilated environment avoiding the loss of water by evaporation, favouring the release of all moisture into the substrate. These characteristics may be favourable in the summer, when the vegetation absorbs the water contained in the substrate and transports it through the leaves, which results in a passive evaporative cooling strategy.

Figure 10 - Different prototypes of alkali-activated binder base.

2.3.2. ICB layer

Expanded black cork board, also known as Insulation Cork Board (ICB) is a natural eco-friendly material made from cork granules.

ICB is a lightweight material with thermal and acoustic properties. Therefore it can contribute to insulate buildings envelope. As standard board it has a density between 125 - 160 Kg/m^2 and a heat transfer coefficient between 0.037 a 0.040 $W/m^2.K$. Main advantages of using this material are the fact that it is a sustainable material with low density.

Cork tree is from the oak family. It is an autochthonous tree from southern Europe from which the cork is extracted. Cork extraction isn´t harmful to the tree, since the tree returns to produce a new layer every 9 years. ICB results from the agglutination of waste cork granules (falca). The most valuable cork is removed from the tree trunk. Falca is removed from cyclic pruning branches of cork trees. Falca is then crushed and cleaned of impurities, like bark, wood, cork dust, earth or stones. The granules are inserted into an autoclave and subject to thermal treatment at 400ºC with water vapour. This process causes a volumetric expansion of the cork granules and a exudation of a natural cork resin which leads to the agglutination of cork granules, forming pure cork agglomerate. This process doesn´t include any glues, paints or additives. After complete cooling and dimensional stabilization the blocks are cut into boards [15].

The upper layer of the Geogreen modules is made by CNC cutting an 80 mm (3,15 inches thickness) expanded black cork board (ICB) with a density of 160 Kg/m^3 and the shape presented in Figure 11. Each upper plate weights around 650 g, comprising a total weight of around 7 Kg/m^2.

It has enough mechanical strength to withstand the substrate and vegetation load. As previously mentioned this material also has also low thermal conductivity and good acoustic insulation properties. Therefore, the thermal and acoustic contribution of the Geogreen system to buildings envelope is analyzed further in Chapters 7 and 8.

Figure 11 - Geogreen module prototypes

2.3.3. Plants selection

Plants insertion was designed to be done individually after the assembly of all modules. The selected vegetation must be adapted to the local climate, be adapted to local conditions of exposure (e.g. sun, semi-shade or shade) and weather conditions (e.g. wind, rainfall, heat, drought and frost). Preference should be given to autochthonous or native plants with low irrigation needs and resistance to severe or extreme climatic conditions.

The system has some limitations regarding the type of plants to be used, given that its configuration conditions the growth of the vegetation and limits the development of the roots. For this purpose, the most appropriate species should be analysed for the system.

The study of plant species is outside the scope of the work presented here. However, in the context of the R&D Project PTDC/ECM/113922/2009, preliminary studies of selection of plant species adapted to the local climate were developed by other researchers.

The above mentioned study was based on the selection of endemic vegetation, adapted to the local climatic conditions of Beira Interior region, Portugal [16]. This study aimed to promote biodiversity, minimize plant adaptation problems and reduce irrigation requirements. The results of this study showed that *Sedum* species survived to watering once per week. Also some of the tested *Thymus* species and *Achillea millefolium* showed a better survival rate than other plant species with three times watering per week. However, most plant species can only resist to a daily irrigation in the first year of growth. From the tested substrates it was concluded that *Siroroof* substrate showed greater results in most plant species [16].

To prepare a real climate test setting (Figure 12) plants were inserted in the openings individually (Figure 13). The substrate used was Siroroof. There was some substrate loss during the installation process due to the modules vertical position. Although, there wasn´t substrate loss after the installation period. This may result from the fact that this substrate has good density and plants had their roots already developed.

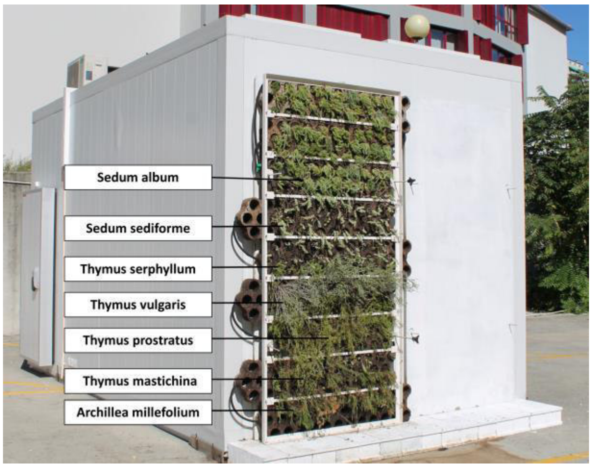

Figure 12 - Plant selection for thermal analysis in real climate testing

Figure 13 - Plant insertion into the Geogreen module in vertical positioning

Although this thematic wasn´t part of this study, it was clearly noticed that plants showed loss of vitality along time. This may be caused by the exposure to low temperatures and their vertical positioning. However further studies should be done to identify the exact cause.

One problem identified is that plants normally grow towards the light and upwards. To achieve it they need to grow 90 degrees to the wall and then turn another 90 degrees to aim skywards. This creates a bend in the plants, making them weak, and braking easily [17]. Therefore, further studies would need to be done to assess the most appropriate plants to be used and how this problem could be addressed.

To minimize this issue an alternative design was proposed (Figure 14). Instead of having openings perpendicular to the vertical surface these could form an angle, allowing to support better the substrate and plants.

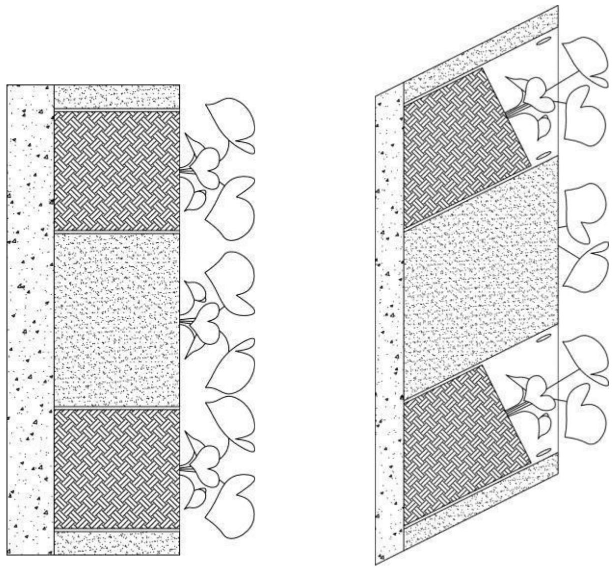

Figure 14- Section of Geogreen modular element, including perpendicular openings (left) and an Inclination of its openings (right).

2.3.4 Irrigation system

The aim of this system is to make an efficient use of water, avoiding its waste. An irrigation system is proposed to feed all plants whenever needed. It consists on the insertion of a 16mm drip irrigation tube along the middle row of each module. For this purpose it can be used a porous hose that sweats water along its entire length which has a slow water consumption rate. It is placed closer to the alkaline activated base to increase its water absorption and slowly moisten the substrate. This solution can be used either in roofs or walls. The irrigation system must be associated with an automatic control to irrigate only when needed. Additionally can be installed sensors that measure the moist percentage in the substrate and allow an adequate water management.

An example of a prototype wall with Geogreen modules is shown below (Figure 15). In this case the modules aren´t cut to be reused and the irrigation tube is just set continuously along the entire surface. In normal conditions the irrigation tube can have T connectors at the end of each row and include a vertical pipe along each end. In larger surfaces connectors can also be placed along the lines.

In case one module needs to be removed for maintenance purposes the irrigation tube can be cut and connectors can be placed to reassure the irrigation system continuity.

In terms of irrigation needs it depends on several variables like, type of plants used, local climate conditions, surface solar and wind exposures, etc. Additionally, the excess water can be collected by gutters at the ends of the cladded surface. The implemented system may include a rainwater storage system. This water may be stored, treated and introduced into the irrigation system.

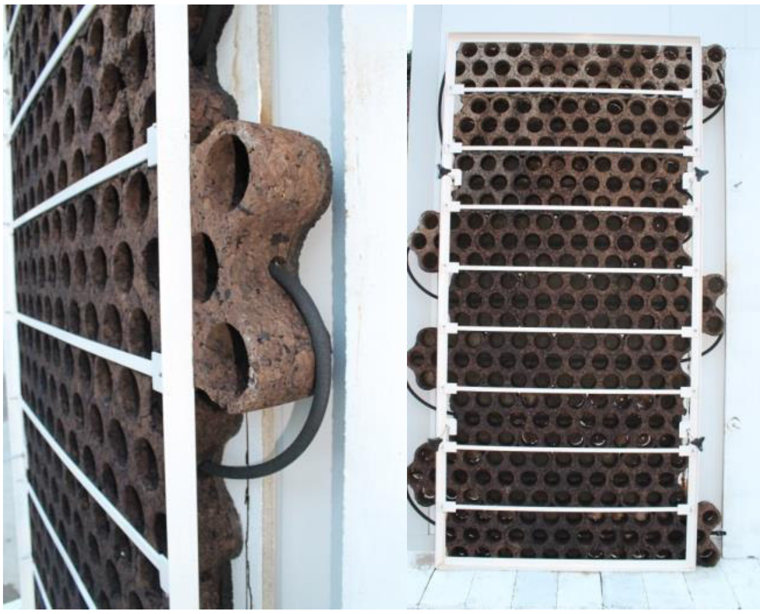

Figure 15 - Geogreen wall irrigation system

2.3.5 Fastening system

This study aims to identify the most appropriate anchorage system to support the Geogreen modules when applied as a green roof or as a green wall. For this purpose several principles are considered. Therefore, the proposed anchors must:

- Transfer all actual loads to the building structure;
- Allow a quick and easy fixing process;
- Allow the modules to be independently supported;
- Consider the modules removal for maintenance purposes;

- Take into account that the aesthetics isn´t compromised by the fastening components;
- Be suitable for concrete roof structures as well as for concrete or masonry wall structures;
- Be placed in the gap between modules;
- Be suitable either in the horizontal or vertical position.

The structural analysis consists on the identification of the working loads in form of actual loads to be applied to the anchors and determination of how loads are transferred from the anchor to the structure (tension, shear, bending or a combination of these). This study doesn´t include a complete structural analysis considering the ultimate and serviceability limit states of the supporting building structure (roof or wall). Also, a specific application into a building is not part of this study.

Loads

Loads can be applied to anchors in a variety of ways – tension, compression, shear, bending or a combination. Their capacity in these directions varies significantly. It is therefore important to identify these loads and determine the limitations of the proposed anchors. Working loads were determined based on Eurocode 1: Actions on structures [18, 19]. For this analysis it was assumed a 14x10m building with 3 floors (9m high) and flat roof, located near the sea coast in Portugal. The area of influence determined for each anchor is 0.04719m^2 which is relatively small (Figure 16).

Loads were calculated for two scenarios, a Geogreen wall where the modules are fixed vertically and a Geogreen roof where modules are fixed horizontally.

When positioned vertically the modules are subject to vertical loads like self-weight and horizontal loads as wind pressure (Figure 17). Vertical loads are transferred to the anchors as pure shear or as bending loads. Self-weight of Geogreen modules was determined in dry and saturated conditions. Anchors bending capacity is very low, therefore these loads should be transferred as pure shear wherever possible. In this case the bending moment will be relatively small because the eccentricity of this force is negligible. The horizontal load is wind pressure which acts in the form of tension or compression.

When the modules are positioned horizontally they are subject only to vertical loads as self-weight and wind pressure (Figure 18). Wind loads are normal to the roof structure and acts in the form of tension or compression. However these loads are balanced by the self-weight of Geogreen modules.

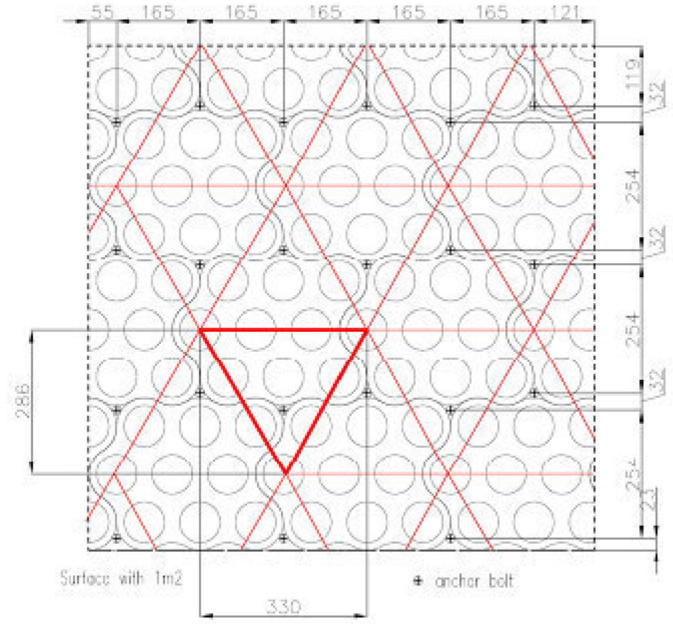

Figure 16 - Geogreen modules arrangement in 1m^2 with possible location of anchor bolts and their area of influence

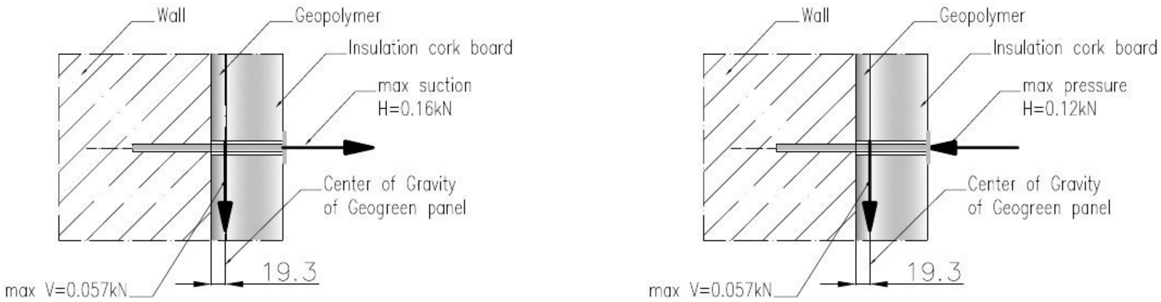

Figure 17 - Final values and position of forces - Geogreen as green wall

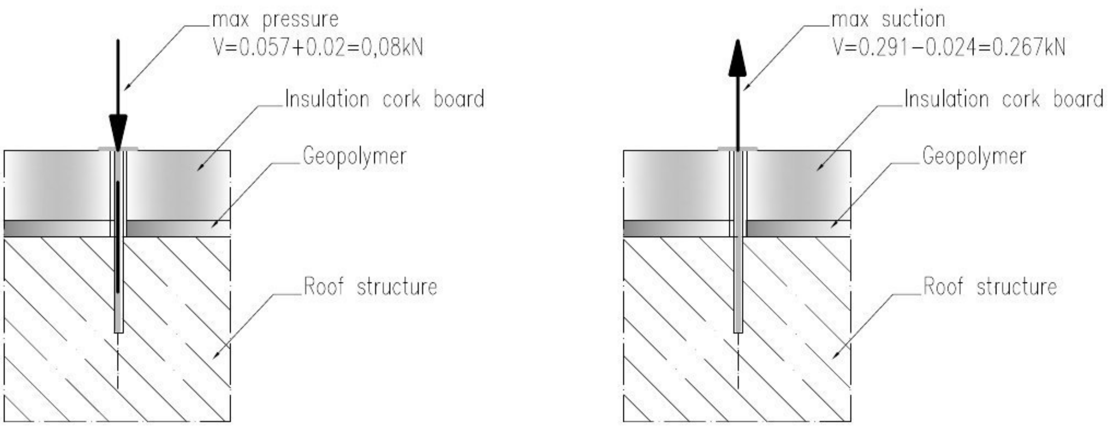

Figure 18 - Final values and position of forces - Geogreen as green roof

Solutions

Based on the assumed principles, two solutions were proposed as fastening systems. The structural verification of these solutions was conducted using PROFIS Anchor 2.0.7 software provided by the HILTI. The selected solutions are appropriate for concrete, lightweight concrete, solid brick or hollow brick.

A first solution is proposed using IDMS/IDMR fasteners (Figure 19), a typical stainless steel insulation fastener suitable for concrete and brick walls (Solution 1). It is corrosion and fire resistant. This solution requires a drill hole of 8mm to be opened first and then each fastener can be applied simply by hammer (Figure 20). Through the calculation of allowable loads it was identified that an IDMS/IDMR version 9/12 fastener can be applied in the opening between modules.

Figure 19 - IDMS/IDMR insulation fastener.

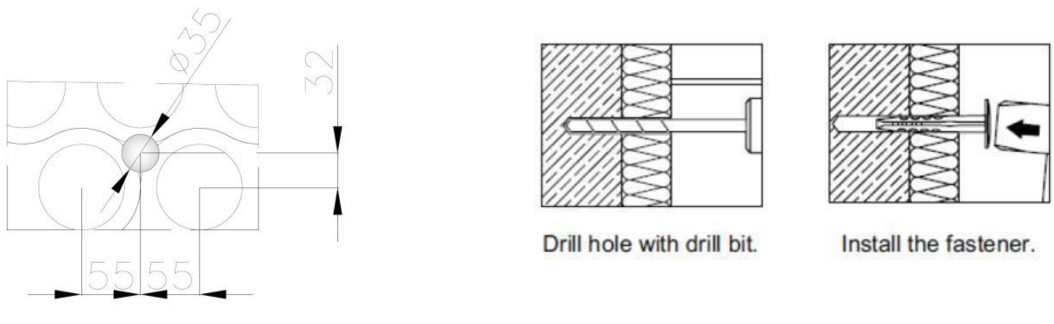

Figure 20 - Details of anchorage system using IDMS/IDMR version 9/12.

A second solution is proposed using Hilti anchor HUS-H 8mm (Figure 21) with a face steel plate (Solution 2). Two types of steel plates were tested with this solution. A 47mm circular steel plate (Option A) and a triangular steel plate (Option B) covering the space between openings (Figure 22).

Figure 21 - Hilti anchor HUS-H 8mm

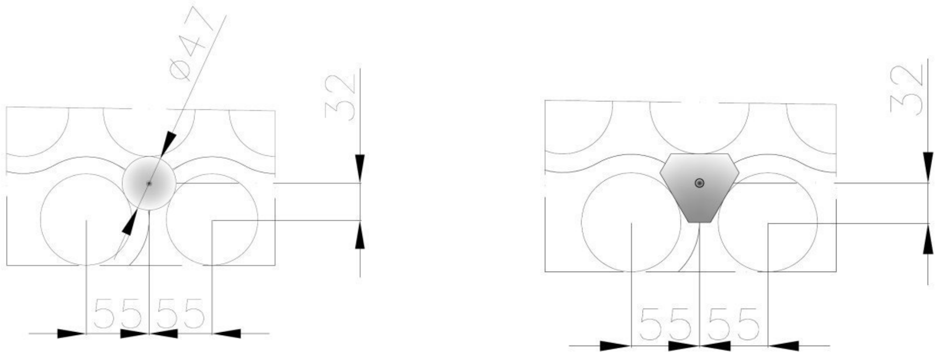

Figure 22 - Details of anchorage system using Hilti anchor HUS-H 8mm with circular plate (left) and with triangular plate (right).

Simultaneously, because the working forces are relatively small, a reduced number of the fasteners were also checked. In this case were considered only 3 fasteners for 1 Geogreen panel as shown in Figure 23.

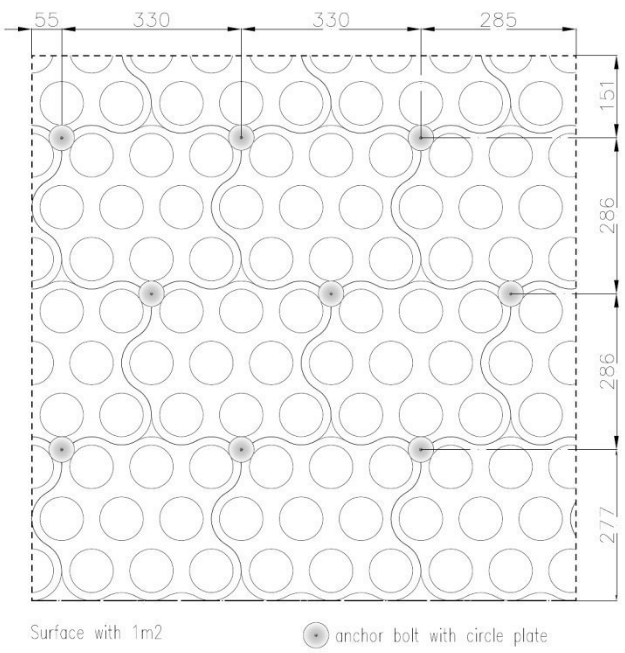

Figure 23 - Solution 2 with 3 fasteners for 1 Geogreen panel

The results demonstrate that Solution 2 with 3 fasteners using Hilti anchor HUS-H 8mm and circular plate is the most effective. Therefore, a prototype was developed to demonstrate how the modules are fastened vertically (Figure 24).

Figure 24 - Fastening prototype for Geogreen wall system

In case these steel plates become too visible, the surface aesthetic can be improved by using brown plastic caps covering the steel plates with the same shape, similar to how the furniture screws are masked. However this may not be a major concern as the support elements will be hidden as soon as plants grow to cover the entire surface.

2.3.6 Detailing

Considering the complexity of its form details of Geogreen wall are presented. Modular elements are cut in the boundaries. A corner element can be placed to allow the system visual continuity (Figure 25, left).

On the top of the green surface a metal capping can be placed to avoid water to penetrate between the green wall and the support surface (Figure 25, right).

When connecting with the floor a draining material like pebbles can be placed underneath the Geogreen wall allowing excess water to drain into the soil. In case there is a cladding material in the floor a gutter can be placed on the lower part of the wall (Figure 26).

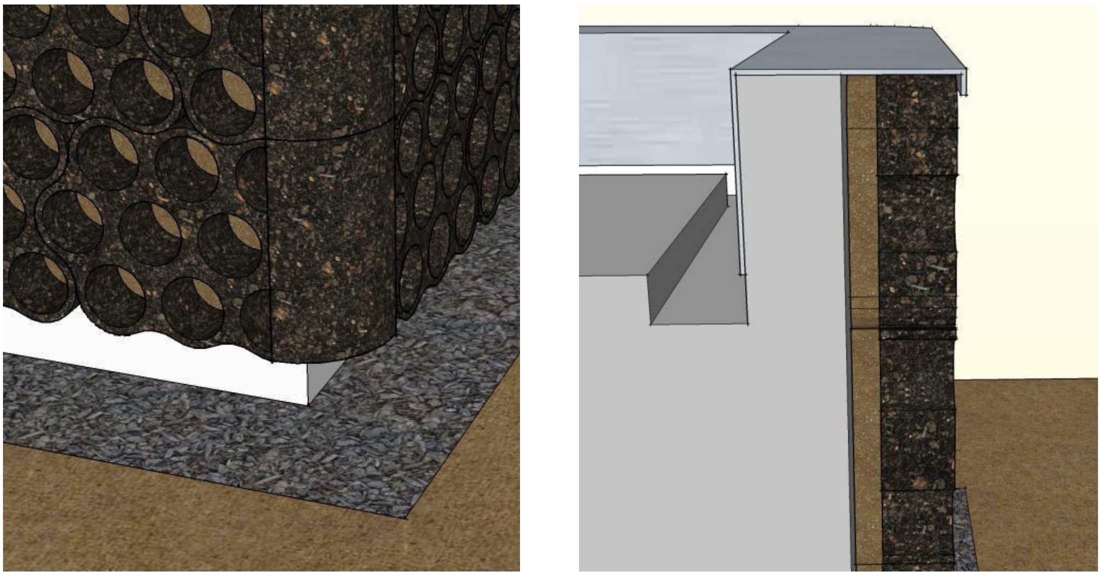

Figure 25 – Corner connection (left) and top wall capping (right).

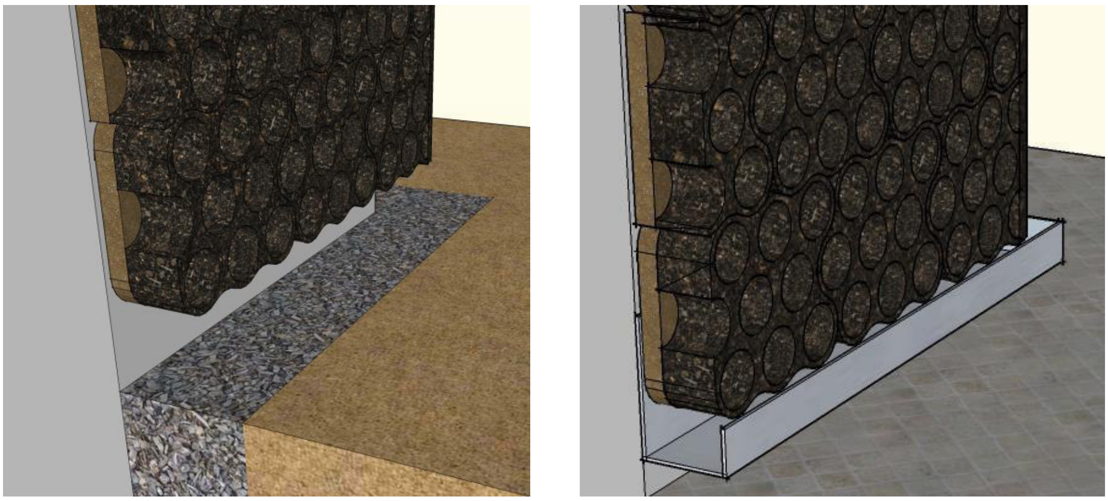

Figure 26 - Lower connections for Geogreen green wall.

2.3.7 System weight

The Geogreen system when fully assembled has an approximate weight of 60 kg/m^2. This weight fits the average values of modular living wall systems. Also its thickness and weight fit into extensive roofs category. Each module (without vegetation and substrate) weights around 3.5 Kg.

The average total weight of each module including substrate and plants is about 5,650 kg, divided as follows: 2,750 kg for the alkali-activated base, 650 g for the ICB upper layer and 2,250 kg for the substrate and plants.

An analysis of weight relation between Geogreen components enables to identify which elements have a major influence on the system weight (Figure 27).

From this analysis it can be identified that the component with the greatest impact on the system weight is the substrate (63%). This is followed by the alkali activated board (23%) which represents almost a third of the substrate weight.

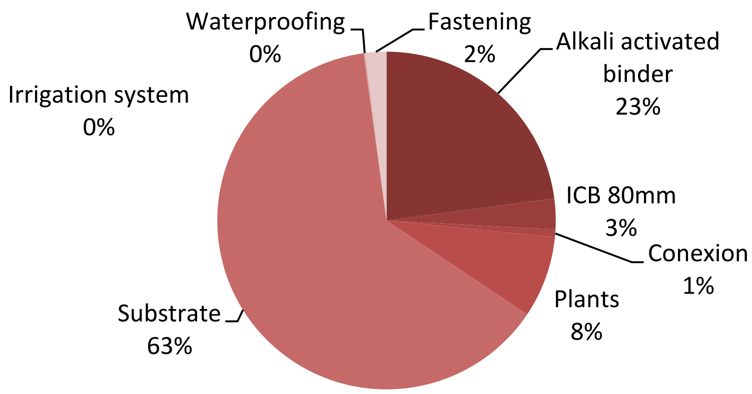

Figure 27 – Comparative weight between Geogreen system components.

The system comprises a low weight substrate appropriate for green roofs (Siroroof), based on humus with 60% of organic matter and 40% inorganic elements. Despite all, from this analysis it is evident that the substrate has a major impact on the modular system weight.

New strategies could be implemented to reduce substrate weight. The depth of substrate may vary depending on the plants used. Several species of sedum have a high resistance to different environments and have a small root system. New examples of green roof systems use sedum blankets and lightweight nets as growing medium allowing plants to penetrate its roots. Also the removal of substrate could be complemented by the addition of nutrients in irrigation water.

Surprisingly, the alkali-activated board represents less than one quarter of the system weight. Alkali-activated binders are usually materials with high density. However, recent studies demonstrate that the density of these materials can be reduced with the addition of low weight aggregates, like granulated cork, or aluminium powder and hydrogen peroxide to produce foamed lightweight materials [20].

2.3.8 System Cost

The cost of Geogreen prototypes was estimated considering all its prototype components. There isn´t still an industrial production process behind this solution which makes it more difficult to compare it with other systems existing on the market. The cost of each component was analysed according to the current market values. From this cost analysis it can be confirmed that the Geogreen system materials have a global cost of 278€/m^2.

The proposed system may fit into the costs identified by Perini et al. for living wall systems (LWS). This author refers how living wall systems cost can vary significantly. They can start from 100-150 €/m^2 with HDPE planted boxes and reach to 1200€/m^2 when using foamed substrate. Their cost depend significantly on the location where it is to be installed, the surface conditions, its height and amount of connections needed. In fact living wall systems are relatively new and expensive due to the maintenance needed (irrigation and nutrients), materials used and design complexity of these systems [21]. It is also important to mention that LWS durability varies significantly. While a LWS based on felt layers has an average life expectancy of ten years, a LWS with planter boxes can last until fifty years [21]. This has a significant impact on the life cycle cost of these systems. Despite their cost, green walls can be economically promising as noise attenuation strategy with additional aesthetic benefits [22]. Several studies demonstrate also that extensive green roofs and living wall systems have higher initial costs than other conventional building systems. However, the life cycle cost analysis of these systems shows that they have several social, economic and environmental benefits which minimize their cost impact on buildings life cycle [22, 23, 24, 25]. A comparative cost analysis between the Geogreen system components was performed in order to identify which elements have a higher impact on the system cost (Figure 28).

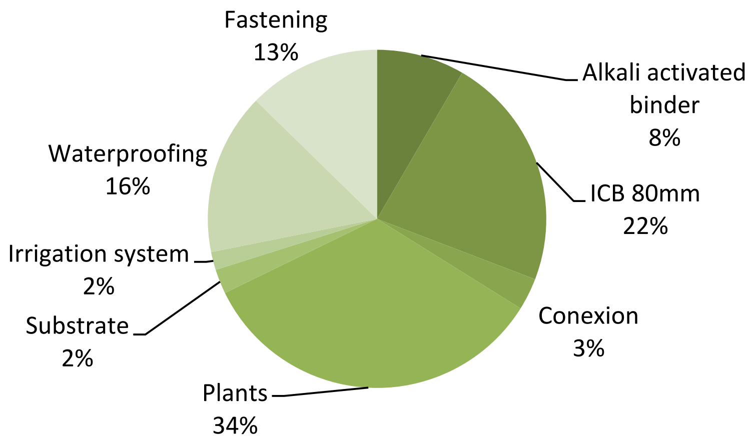

Figure 28 - Comparative cost between Geogreen components

From the obtained results is becomes notorious that the cost of natural plants (34%) have a major impact on the global cost of the Geogreen system. In fact if adapted plants are produced locally this may influence the cost of each plant and consequently the cost per m^2 of the system. An alternative would be also to redesign the system to reduce the amount of plants per m^2 allowing them to grow more. This may affect the period needed to obtain a full coverage of the wall, and also result on a reduction of vegetation maintenance. Further information would be needed to perform a life cycle cost analysis of this system.

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Chapter 5

Design of alkali-activated materials for a modular green wall and green roof system

This chapter consists of the following article:

Design of alkali-activated materials for a modular green wall and green roof system

Manso, M., Castro-Gomes, J.P.

RICON 17, Remine International Conference, 25-27 October, 2017

Design of alkali-activated materials for a modular green wall and green roof system

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Abstract. This study presents the work developed with alkali activated mixtures to be used as component of a new modular green wall and green roof system (Geogreen). The aim is to find the most appropriate composition of alkali-activated mixture to maximize water absorption and porosity and also find a good mechanical strength with reduced density. Alkali-activated mixtures were produced using two precursors, mine waste mud from Panasqueira mine (W) and ground waste glass (G) and two alkaline activators, sodium silicate (SS) and sodium hydroxide (SH). A ventilated oven was used to speed up the curing process. Variables as percentage substitution of W per G, molar concentration of SH, cure length and temperature, were tested to identify the reference mixture. After these tests different percentages of aggregates as sand (S), expanded cork granules (C) and expanded clay (A) were added to reference mixture (REF). Results indicate that S25 obtained the maximum compressive strength of 35MPa after 7 curing days. However 30% compressive strength loss is observed after immersion of this mixture in water for 24h. Capillary absorption coefficient can reach to 4,77 $kg/m^2.h^{0,5}$ with C25 and to 4,11 $kg/m^2.h^{0,5}$ with S25. Also C50 enables a 20% density reduction compared to REF.

1 Introduction

1.1 Background

The construction sector is the main waste producer in European Union (EU) representing 35% of total produced waste. Mine and quarrying comes just after representing around 28% of total waste production [1]. Therefore it is important to find alternative applications for construction and mine waste, promoting their recicling and reuse.

Panasqueira mine in Portugal generates several tons of coarse aggregate and waste mud every year [2]. Recent research indicates that mine waste mud from Panasqueira mine is rich in silica and alumina and show good reactivity with alkaline activators like sodium silicate and sodium hydroxide allowing to produce alkali-activated binders [3].

Studies indicate that alkali-activation can be improved by mixing Panasqueira mine waste mud with other sources of silica [4, 5, 6].

Also lightweight aggregates as expanded clay, expanded polystyrene (EPS) or granulated cork are also being tested in concrete mixtures [7, 8].

1.2 Modular system design

Environmental conditions of urban areas are becoming deteriorated, due to crescent pollution, densification and lack of green areas. In this context, new solutions of green walls and green roofs are being developed to create vegetated surfaces in buildings [9] without any land occupation [10]. In fact they can be used as a potential strategy of urban rehabilitation [11, 12], having several environmental, social and economic benefits [13]. Recent studies focus on green walls and green roofs ability to improve the urban environment by reducing the heat island effect [14], decrease flood risk and air pollution [15, 16], encouraging the fruition of urban areas [17], increase biodiversity [18, 19, 20], and improve quality of life [17]. In a building scale green walls and green roofs can also reduce energy demand for heating and cooling [21, 22, 23] and improve buildings thermal [24] and acoustic envelope [25, 26, 27].

A new modular system (Geogreen) for vegetated surfaces (Fig. 1-3) was designed with the aim of creating more sustainable green roofs and green walls [28, 10, 29]. Based on the reuse of industrial waste, alkali-activated materials are integrated into this modular system with the purpose of absorbing water and slowly release it to the plants, minimizing its irrigation needs.

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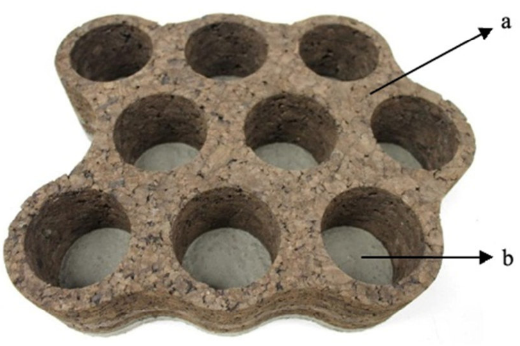

Fig. 1. Geogreen module: with lower layer in alkali-activated binder (a) and upper layer in expanded cork with circular openings (b).

Fig. 2. Alkali-activated binder applied on the back of Geogreen module.

Fig. 3. Geogreen modules in vertical position.

1.3 Goals

This study aims to identify the composition of alkali-activated mixtures which have the best characteristics to be used as a component of Geogreen. The goal is to develop an alkali activated binder that has good mechanical strength and water absorption, porosity, and lower density than conventional alkali-activated binders.

2 Materials and Methods

Several materials make part of the alkali-activated mixtures. As precursors were used waste mud (W) from Panasqueira tungsten mines and milled waste glass (G).

As activators were used sodium silicate (SS) and sodium hydroxide (SH).

Aggregates like, sand (S), expanded cork granules (C) and expanded clay (A) were also added to the mixture.

Waste mud was supplied by Panasqueira tungsten mines from Portugal. It comes in the form of a powder. Glass bottles were supplied by the local municipality. Glass bottles are cleaned and labels removed. Glass is broken, dried and sieved with a 125 µm sieve. Sand is sieved to obtain the desired particles size.

2.1. Materials characterization

Mine waste mud from Panasqueira mines in rich in alumina-silicates and has very good reactivity with alkaline activators like sodium silicate and sodium hydroxide. From the chemical analysis it is evident that mine waste mud is rich in silicon dioxide (52%) and aluminium oxide (11%). Silica and alumina are fundamental for alkaline activation.

Waste glass has mainly silica (74%) in its composition and smaller amounts of oxides of calcium and sodium. Waste glass is milled and sieved under 125µm to be incorporated into the mixture. It is used in the mixture to increase the precursor's percentage of amorphous material.

Table 1. Oxide chemical composition of mine waste mud and waste glass.

	Constituents (%)	
Oxide	**Mine waste mud**	**Waste glass**
SiO_2	51,72	73,93
Al_2O_3	10,53	-
Fe_2O_3	12,93	0,40
SO_3	10,40	-
K_2O	2,68	0,69
CaO	0,87	12,83

As activators were used sodium silicate (SS) D40 and sodium hydroxide with 10-12M molar concentration. In these mixtures was established a ratio of sodium silicate to sodium hydroxide of 4 and a ratio of precursor to sodium silicate of 4,5.

Different types of aggregates like 1-2mm river sand (S), 4-8mm expanded cork granules (C) and 1-2mm expanded clay (A) were used in the mixtures.

2.2 Synthesis of Samples

Precursors were mixed together in a dry state until obtaining a uniform mixture. Activators like sodium silicate and sodium hydroxide solution were mixed together in a mixer for 10 minutes at low speed. After these the precursor mixture is slowly added to the alkali-activator solution. After obtaining good mixture, water is slowly introduced. Finally aggregates are added.

Alternatively aggregates surface can be sprinkled first before being inserted into the mixture. The resulting paste is mixed at a lower rate until uniformity is obtained and then placed into the mold. The paste is manually compressed to ensure full mold filling. The mold is covered with plastic to avoid a rapid moisture loss in the beginning of curing process. Samples were demoulded and left uncovered after 48 hours.

2.3 Compressive Strength

Samples with 40x40x40mm were prepared for compressive strength. Compressive strength was tested using a ELE 3000 kN compression equipment in accordance with EN 196-1 [30], with some adaptations. The compressive strength value was the average of values obtained from six specimens.

2.4 Water immersion

Specimens with 40x40x40mm of each mixture were also produced to identify if mixtures mechanical strength is affected by water. Six specimens of each mixture were tested after a curing period of 7 days. All samples were allowed to cool after curing and then inserted in a tin with approximately 1 litre of water at room temperature for 24h. This was considered the time necessary to get specimens saturated. After each immersion period, specimens were removed from water, dried until constant mass acquired and submitted to a compressive strength test in accordance with EN196-1 [30], with some adaptations.

2.5 Capillarity Water Absorption

Capillarity is defined as the penetration of a liquid into the material by effect of surface tension generated at the water-air-wall pores interface. Water penetration depends normally of the quantity, size, shape and pores connectivity in the material structure. Test samples were prepared according to the Portuguese Specification E393-1993 – Concretes, with some adaptations. Five samples with 4x4x14cm of each mixture were prepared to perform this test. Samples were dried at a constant temperature until constant mass is acquired, then allowed to cool at room temperature. Test samples were inserted into a tray with 5 to 10 mm of water above the underside of the samples. Measurements were made at the end of 3h, 6h, 24h and 72h from the moment samples were placed in contact with water.

3 Results and discussion

Prior to adding aggregates to the mixture, some characterization tests were performed to identify the reference mixture. In this context different molar concentrations, waste glass percentages and curing times were tested.

3.1 Influence of glass substitution on mixtures compressive strength

This analysis is based on a replacement of a percentage of 20% to 30% of mine waste mud (W) by milled waste glass (G). Each result reflects the average value from six specimens per each G replacement value and age. These mixtures were tested after 7, 14 and 28 days at a constant curing temperature of 60°C.

In Fig. 4 it can be observed that for 7 curing days the compressive strength increases with the addition of G content in the mixture. However, the increase of strength is not so marked in longer cures. W70G30 shows even a loss of strength after a 14 curing days. In fact mixture W80G20, with a lower G content, was the mixture that presented a greater increase of strength over time. Therefore this mixture was used forward as reference mixture.

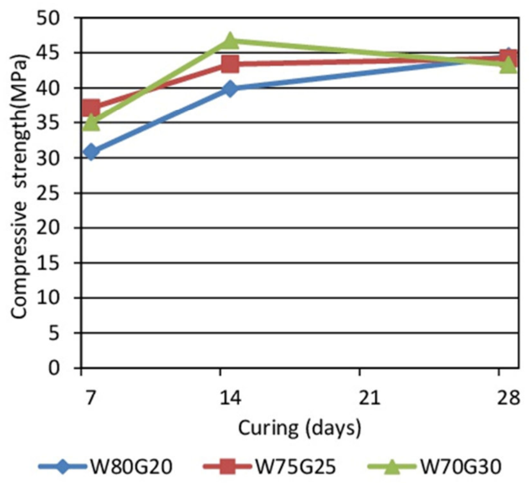

Fig 4. Compressive strength of alkali-activated mixtures with 20% to 30% of W replacement by G.

3.2 Influence of sodium hydroxide molar concentration in compressive strength

Considering that mixture W80G20 demonstrated a better behaviour it was used as reference for the following studies. In this case different molar concentrations of sodium hydroxide were tested to identify its compressive strength with different curing periods (Fig.5). Results indicate that mixtures with 12M present slightly higher compressive strength in shorter curing periods of 7 days. However the results are very similar between 10M and 12M concentrations.

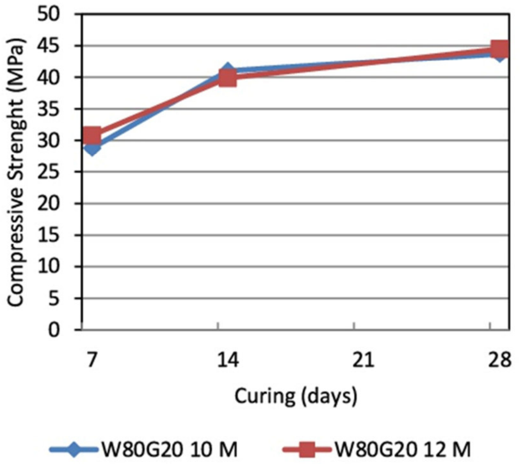

Fig 5. Compressive strength of alkali-activated mixtures with different SH molar concentrations.

3.3 Influence of curing temperature in compressive strength

The influence of curing temperature was also identified (Fig. 6). Curing at 60ºC presents a continue increase of compressive strength along the time. The same doesn´t happen if the cure is increased from 60ºC to 80ºC. Specimens cured at 80ºC show the highest compressive strength, 44 MPa, when cured for 7 days. However there is a 26% loss of strength when curing is increased from 7 to 14 curing days.
If the cure is prolonged from 14 to 28 days the tendency of both mixtures is to increase their strength.

Ideally curing time and temperature should be minimized when possible to reduce the embodied energy of alkali-activated mixture and consequently the CO_2 emissions regarding its production. The results indicate that a good compressive strength is reached at 7 days with a curing temperature of 60ºC.

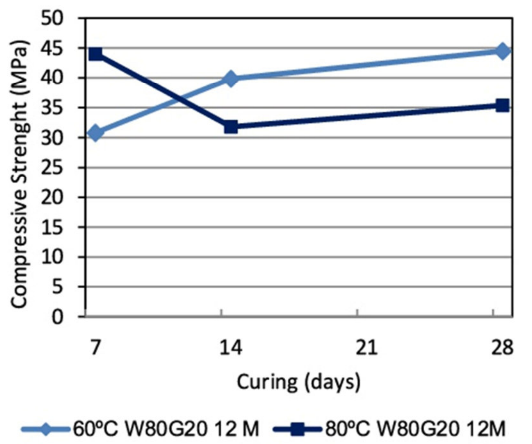

Fig 6. Compressive strength of alkali-activated mixtures with different curing temperatures.

Considering these variables the mixture W80G20 with 20% of G content, a molar concentration of 12M, and a curing period of 7 days in a ventilated oven at 60ºC was the one that presented a greater increase of compressive strength over time. Therefore this mixture was used forward as reference mixture (REF) to add different percentages of aggregates.

3.4 Aggregates influence on compressive strength

Several alkali-activated samples were prepared adding to REF 25% to 50% of precursor's mass of the following aggregates: 4 to 8mm expanded cork granules (C), 1 to 2mm river sand (S), 1 to 2mm expanded clay (A). These mixtures were tested to compressive strength with 7 days of curing at 60ºC (Fig.7).

Mixture S25 was the only one that revealed better compressive strength than REF. This may results from the fact that sand has silica in its composition helping to increase the amount of amorphous material to react in the mixture. However sand was the aggregate that revealed greater loss of resistance when the percentage is increased to 50%. Mixtures with 25C and 50C were the ones with lower compressive strength, 17 and 13 MPa, respectively. These results represent a 45-58% loss of strength compared to REF. However the results are satisfactory for all mixtures given that it is desired to develop a cladding material.

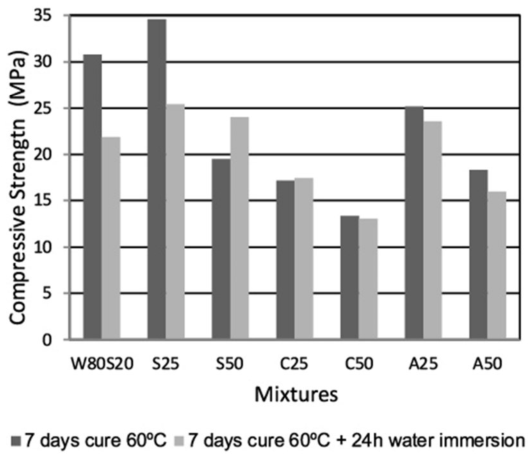

Fig 7. Compressive strength of mixtures with aggregates.

3.5 Effect of water immersion on mixtures compressive strength

Six specimens of the same mixtures prepared to test the influence of aggregates on compressive strength were used for this test. A comparative analysis is shown in Fig. 7. The results indicate that all mixtures tend to loose compressive strength after water immersion for 24h. Only S50 presents a 12% increase of compressive strength compared to REF (W80G20). This increase may

result from the presence of amorphous silica in the sand which also reacts.
It must be pointed out that cork mixtures were the only ones in which the process of water immersion for 24h didn´t affect their compressive strength.

3.6 Influence of aggregates in water absorption by capillarity

Water absorption of these specimens was compared with the reference mixture REF with no aggregates (Fig. 8). Mixture C25 is the one that shows higher water absorption along the time. However S25 shows higher results in the first hours. Regarding the increase of aggregates percentage from 25% to 50% it proves to be detrimental, leading to a significant reduction in capillary absorption capacity in all mixtures. Although expanded clay is a porous material, the blends with this material have been found to have the lowest capillary absorption capacity of all mixtures with aggregates.

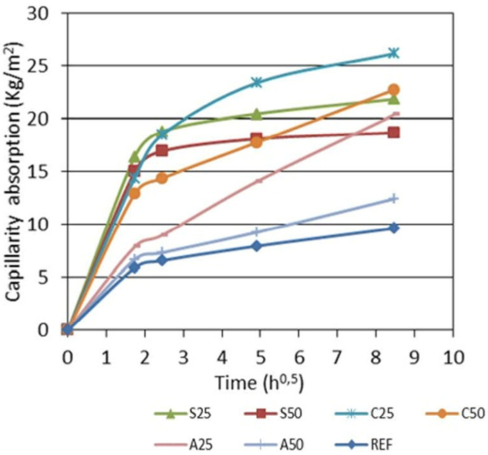

Fig 8. Water absorption by capillarity of alkali-activated mixtures with aggregates.

3.7 Relation between mixtures density and water absorption

By establishing the relation between mixtures bulk density and water absorption coefficient (Fig. 9), we can identify which are the most advantageous for the design of Geogreen modules.

All aggregates contribute to increase the mixture water absorption coefficient (Aw). However the ones with better results are C25 with 4,77 $kg/m^2.h^{0,5}$ and S25 with 4,11 $kg/m^2.h^{0,5}$.

The results indicate that all mixtures with sand, S25 and S50, have higher bulk density than REF. The mixture with expanded clay, A25 and A50, are the ones with lower water absorption.

C50 is the mixture with lowest bulk density, 1,55 g/cm^3 and C25 is the mixture with highest water absorption coefficient.

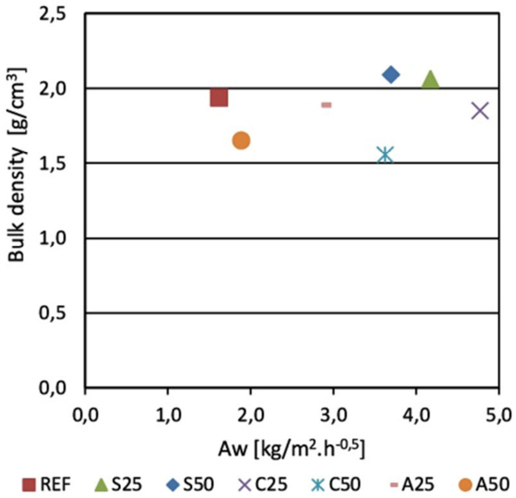

Fig 9. Water absorption coefficient of alkali-activated mixtures with aggregates.

3 Conclusions

Mixture S25 can reach a maximum compressive strength of almost 35 MPa, after 7 curing days at a constant temperature of 60ºC in a ventilated oven. However a 30% compressive strength loss of is observed after immersion in water for 24h.

Capillarity absorption coefficient can reach between 1,89 $kg/m^2.\ h^{0,5}$ for A50 to 4,77 $kg/m^2.\ h^{0,5}$ for C25. Density can be reduced with the introduction of expanded cork granules as aggregates in the mixture. C50 enables a final density of 1,55 g/cm3, which represents a 20% reduction from REF.

Therefore expanded cork granules are considered the most suitable aggregate to add to these alkali-activated mixtures.

Results indicate that alkali-activated mixture C25 that has the most appropriate combination of properties to be used in Geogreen modules. It obtained one of the lowest compressive strength with 17MPa. However in obtained a water absorption coefficient of 4,77 $kg/m^2.h^{0,5}$ and a density of 1,85 g/cm^3.

Further tests could be prepared to identify if the percentage of cork granules could be slightly increased.

These studies were carried within the scope of SFRH / BD / 98422/2013 PhD Grant funded by the Foundation for Science and Technology (FCT) and Human Potential Operational Program (POPH). The tests were completed in the construction technology and mechanic test laboratory of University of Beira Interior. All studies were developed at C-MADE, in the University of Beira Interior. This work appears in the sequence of the research project "Waste Geopolymeric binder-based natural vegetated panels for energy-efficient building green roofs and facades".

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Chapter 6

Thermal analysis of a new modular system for green walls

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Thermal analysis of a new modular system for green walls

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System design
Thermal performance

ABSTRACT

Green walls can protect building envelope from surrounding environment while contributing to improve buildings design and thermal performance. The design concept of a new modular system (Geogreen) for vegetated surfaces has been developed to create more sustainable green roofs and green walls.

This paper aims to present the study of Geogreen system thermal performance in a Mediterranean climate. This work is based on the evaluation of local meteorological conditions in three different periods. The Geogreen system is tested in an exterior test cell, comprising a reference wall and a wall covered with Geogreen modules. The analysis is based in the interior surface temperatures and interior surface heat fluxes of two compartments with the same dimensions and thermal characteristics.

Resuts show that Geogreen system contributes to: reduce maximum interior surface temperatures and increase minimum interior surface temperatures up to 7 °C; mitigate heat transfer, reducing maximum income heat flux by 75% and maximum outgoing heat flux by 60%; enhance thermal insulation of a wall; and increase thermal delay between the exterior and the interior. These aspects can lead to reduce and shift air-conditioning power loads and to improve buildings thermal performance.

1. Introduction

Green wall is the common term to refer to all forms of vegetated wall surfaces. Green walls can be subdivided in two main systems: green facades and living walls. There is an evident distinction between green facades, where usually climbing plants grow along the wall covering it, and the most recent concepts of living walls, which include materials and technology to support a wider variety of plants, creating a uniform growth along the surface. Green facades can be classified as direct or indirect. Direct green facades are the ones in which plants are attached directly to the wall. Indirect green facades include a supporting structure for vegetation. Living wall systems (LWS) can be classified as continuous or modular, according to their application method. Continuous LWS are based on the application of lightweight and permeable screens in which plants are inserted individually. Modular LWS are elements with a specific dimension, which include the growing media where plants can grow. Each element is supported by a complementary structure or fixed directly on the vertical surface [1].

Nowadays green wall systems are becoming popular [2] though they are still evolving and more knowledge on some of their particular impacts is required. The traditional composition of plants and soil substrates have been combined with new technologies in order to improve their performance and enhance the benefits allowed with these systems [3].

The final Report of the Horizon 2020 Expert Group on "Nature-Based Solutions and Re-Naturing Cities" enhances the attractiveness of green walls among other nature-based solutions, as in the long run they can be more cost-effective. As pointed out in this Report there are a number of new approaches for the implementation of nature-based solutions including integrating living systems with built systems through innovative combinations of soft and hard engineering. Heat stress in cities can be addressed by increasing green spaces and using green walls and green roofs. These measures could reduce temperature by up to 10 °C in Mediterranean areas. All of these approaches can also contribute to decrease flood risk and air pollution hazards, reduce energy demand in buildings (by 10–15%) and improve quality of life [4].

Green walls can be a smart approach of urban rehabilitation, contributing to the integration of vegetation in the urban context without land occupation [5], encouraging the fruition of urban areas [6] and improving buildings design and performance.

Green walls can make part of a sustainable strategy for the urban environment [7,8]. In fact the integration of vegetation in urban areas has several environmental benefits [9], contributing to: improve air quality [10], through the absorption of CO_2 [11] and the retention of dust particles and heavy metals [12]; mitigate the urban heat island effect [13], influencing the local climatic

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conditions (temperature and humidity); and biodiversity [14–16].

At the same time, the integration of vegetation in the urban environment makes a positive impact on human health and has economic benefits [17]. The presence of green areas influences aesthetically the surrounding urban area and contributes to increase property value [18].

Green wall systems can also protect building envelope from local climate and surrounding environment. They have the ability to function as a complementary acoustic protection [19,20], contributing to improve comfort of interior spaces. In fact, green walls can be integrated in buildings among several passive design solutions [21] as a strategy of evaporative cooling [22]. Most importantly, they can shadow the envelope [11,23–25], avoid overheating and degradation of coating materials, while contributing as an additional thermal protection [26–30], minimizing buildings energy demand for heating and cooling [13,31,32].

Green wall systems thermal contribution depends of several factors, such as: the type of vegetation and plants characteristics (e.g. leaf shapes, stage of development, colours, forms, solar transmittance, vegetation coverage percentage) [23,22,33,29,34]; type of substrate and its moisture content [23,22]; the system used (green façade or living wall, their composition, materials used, distance from wall), building characteristics (solar orientation, wind exposure) [34] and local climate conditions (e.g. external temperature, humidity, wind, rainfall). So, it is important to understand the context and conditions in which each green wall system is applied and how it can improve buildings energy performance [26].

In Mediterranean regions buildings are exposed to high solar radiation in summer and subjected to high daily and annual temperature variations. Therefore, insulating the envelope can contribute to reduce the impact of solar radiation in summer and protect it from large temperature differences between the interior and the exterior [35]. Some studies have been conducted in Spain and Greece [21,22,34,35] on the thermal performance of green facades in the Mediterranean climate. However, the energy performance of living walls is still a subject relatively new [36].

Thus, the present study aims to analyse the influence of a new modular green wall system on the thermal behaviour of building envelopes and its impact on their indoor environment in a Mediterranean climate. The thermal analysis is performed for a bare wall and the same wall covered with the modular system. The work is developed for 3 different periods in the central region of Portugal, between September and December 2013. A comparison regarding the bare wall and the covered wall is attained via an experimental setup. Results refer to temperature and heat flux values obtained in the interior surface of both walls.

2. System design

The design concept of a modular system (Geogreen) has been developed with the purpose of creating a more sustainable system for green roofs and green walls (see Fig. 1). This solution emerged from the R&D project PTDC/ECM/113922/2009 in which the authors were part of the team. It occurred in University of Beira Interior, Portugal between 2011 and 2014 and was partially funded by the Portuguese Foundation for Science and Technology (FCT). Its development makes part also of a Ph.D. study funded by the scientific research grant SFRH/BD/98422/2013, supported by FCT and POPH/ESF financing program. The presented modular system is patented (PT106022A) and was prized in Portugal and USA for its innovation in design, use of local and recycled materials and integration of climate adapted plant species.

The development of Geogreen system is based on the purposes to minimize its environmental impact and irrigation needs,

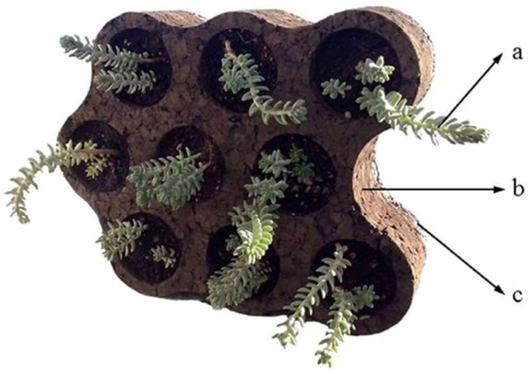

Fig. 1. Geogreen modular system design with plants and substrate. a. Adapted plant species; b.Upper plate in expanded cork board; c. Base plate in geopolymer binder.

enabling its suitability to different surfaces in new buildings and retrofitting, allowing the substitution of each module individually and improving buildings thermal performance [37,38].

The Geogreen system is designed to be more versatile than existing green roofs and green walls, allowing the creation of either green roofs or green walls, or both. The application process allows modules to remain locked together. However, in vertical or sloped surfaces, the system may include a support structure inserted in the voids between modules (Fig. 2), allowing its continuity and a reinforcement of its stability. The modular system materials selection is based on the reutilization of mine waste materials to develop alkaline activated binders (geopolymers), combining natural local materials (like expanded cork) with the insertion of endemic vegetation resistant to dry mesomediterranean conditions [37]. The Geogreen modules comprise a geopolymer base plate and an Expanded Cork Board (ICB) upper plate (see Fig. 1). The base plate is made of geopolymeric binder using a blend of mine waste mud and other recycled alumina silica rich waste materials. By increasing the water absorption capacity of the geopolymer plate, the system is able to absorb water and

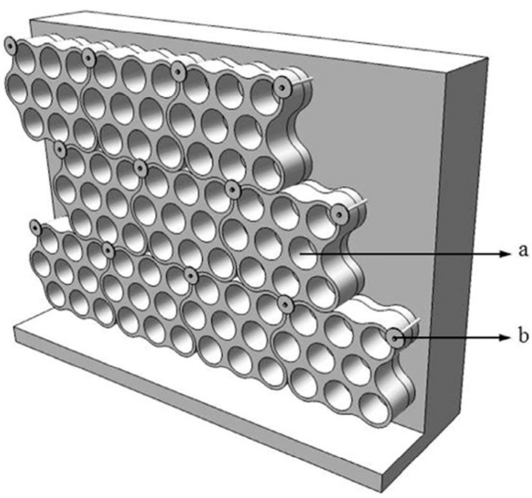

Fig. 2. Geogreen modules in vertical position with interlocking system. a. Geogreen modules (empty of soil and plants); b. Support elements.

slowly supply it to the plants, minimizing water loss and irrigation needs. The upper plate is made of Expanded Cork Board (ICB), a lightweight natural insulation and sustainable material made from the agglomeration of expanded cork granules [39], with adequate structural resistance to support the substrate and plants in the designed circular openings.

With the inclusion of these materials, the system aims to reduce heat loss through the envelope during winter, and protect the envelope from direct solar radiation during summer, avoiding excessive thermal gains that would overheat the interior.

3. Experimental campaign on the energy performance of a green system in walls

3.1. Materials and methods

Real climate tests were performed in Covilhã, Portugal, to determine the thermal performance of Geogreen system. Covilhã is located in Beira Interior Region which has a dry mesomediterranean climate, characterized by a dry and hot season and a cold temperate season, with a large thermal gap between summer and winter seasons. An outdoor test cell was built for this purpose in the University of Beira Interior facilities (see Fig. 3). The test cell is located on the top floor of an exterior building turned into a valley. The setting has no projected shades along all day (see Figs. 4 and 5).

The outdoor test cell is 5.10 m long, 3.10 m wide and 3.10 m high. It is subdivided into three compartments. The hall and two test compartments, each one with a removable panel in the south oriented wall and another in the roof. Each compartment has an individual access to the entrance and an individual air conditioning unit set. The installation of removable panels allows the analysis of different materials for walls and roofs, by comparing a reference wall with a new one. The entire test cell was built with 14 cm sandwich panels with polyurethane foam covered by 1 mm painted steel sheets in both sides. All doors and openings are made with the same materials but with 10 cm thickness. A rubber strip was installed in the edges of each opening to avoid any thermal losses.

This unit was used in this test by installing two different materials in south oriented walls (see Fig. 6). In compartment one was installed a base panel and in compartment two was installed an identical panel covered by the Geogreen modules. Both base panels are made of cement bonded particle boards in grey colour,

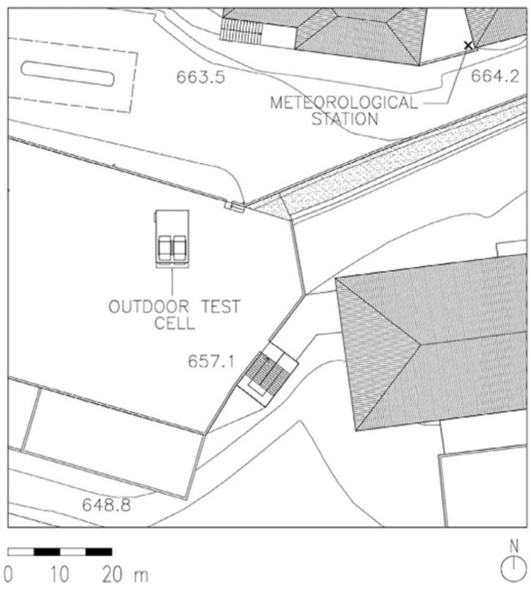

Fig. 3. Exterior test cell localization and orientation.

Fig. 4. Exterior test cell: North view.

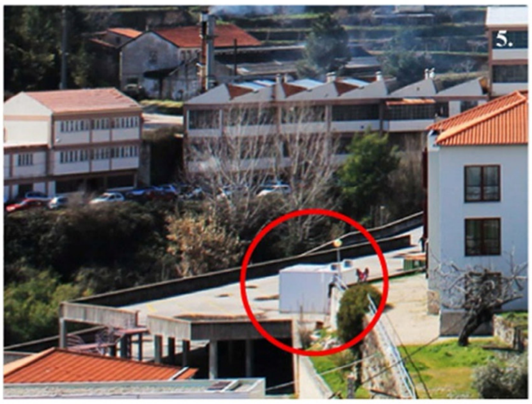

Fig. 5. Exterior test cell: South view.

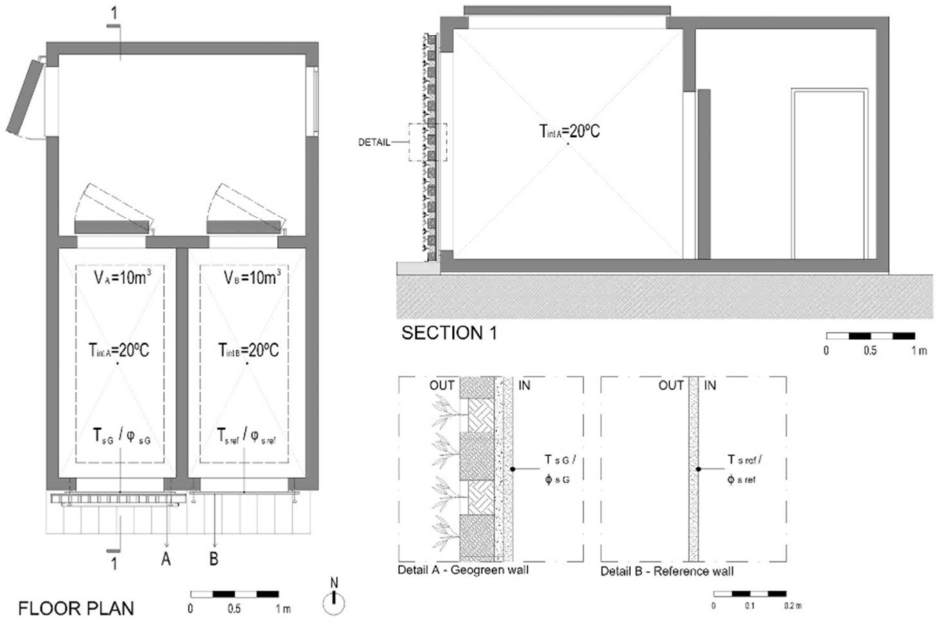

Fig. 6. Test cell plant and section with probes positioning. A. Geogreen wall; B. Reference wall.

based on a compressed dry mixture of pine wood particles and cement, with 22 mm thickness and 0.22 W/m °C thermal coefficient [40]. Each panel was painted with a white waterproofing paint to avoid any water absorption.

Real climate tests comparing the bare wall (compartment A), named as reference wall, and a bare wall covered with Geogreen modules in different circumstances (compartment B), identified as Geogreen wall, were performed in this outdoor test cell between September and December 2013. Each compartment includes an independent air conditioning unit. Both air conditioning units were turn on with a set-point temperature (T_{int}) of 20 °C.

The weather conditions were analysed based on a weather station, model DAVIS Vantage Pro2 wireless with fan 6153, installed nearby. Results of local meteorological data as exterior ambient temperature, relative humidity, rainfall and solar radiation were measured automatically and gathered every 30 min.

Interior conditions in each compartment were analysed by thermocouples type T and heat flux sensors located in the centre of panels. The thermocouples measured the interior surface temperature [°C] of reference wall ($T_{s\ ref}$) and Geogreen wall ($T_{s\ G}$). The heat flux sensors measured the heat flux [W/m²] in the interior surface of reference wall ($\varphi_{s\ ref}$) and Geogreen wall ($\varphi_{s\ G}$). Data was measured every 10 min and collected in a GRANT Squirrel SQ2040 series datalogger.

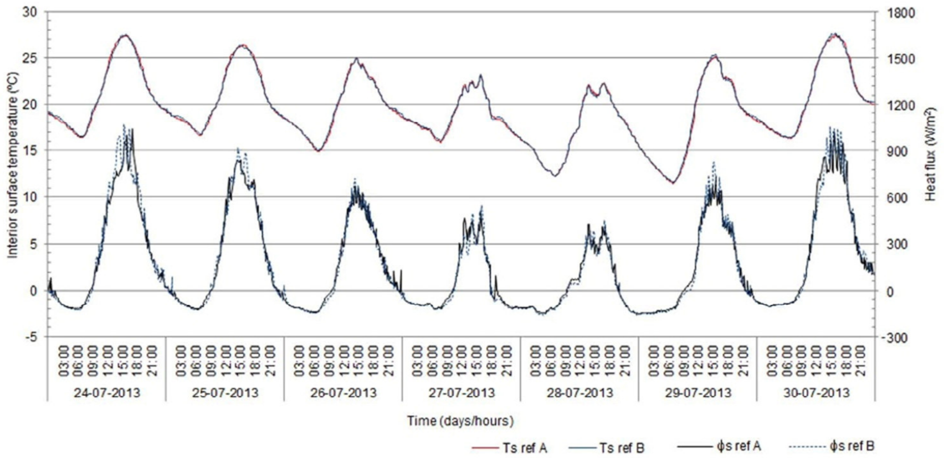

Fig. 7. Calibration test of base panels.

3.2. Calibration

Prior to the installation of any other material, a calibration test was settled on the base walls of each compartment. This test was established in order to make sure that both compartments (A and B) had similar thermal conditions.

The calibration test revealed that compartments A and B showed identical thermal conditions (see Fig. 7). In both walls the maximum interior surface temperature reached to 27.6 °C (around 3 p.m.) in the last day. The minimum interior surface temperature only reached to 11.5 °C (around 7 a.m.). The results demonstrate how the reference wall has more thermal gains during the day and thermal losses at night.

After calibration, the Geogreen modules were installed over the base panel of compartment A without any air gap in between to be able to identify how the modular system can complement the wall thermal insulation and thermal mass. The roof openings in both compartments remained sealed with the insulation panels to avoid any thermal loss. A first test was carried to compare the thermal behaviour of reference wall with the wall covered with Geogreen modules without any vegetation and substrate in the openings (see Fig. 8). This first test (Period 1) was conducted between September 2nd and 11th 2013.

The second test (Period 2) intended to compare the thermal performance of reference wall with the Geogreen wall covered with vegetation and substrate. The analysis was performed during early autumn, between October 7 th and 20th 2013 (see Fig. 9).

A third test (Period 3) was conducted in order to compare the thermal behaviour of reference wall with Geogreen wall, covered with vegetation and substrate, in a period with lower exterior temperatures and less solar radiation. The analysis was performed between November 26th and December 9th 2013.

3.3. Vegetation selection and irrigation

The vegetation installed in Geogreen modules was selected according to a previous study of herbaceous and shrubby associations adapted to local climate conditions. This study was conducted in Instituto Politécnico of Castelo Branco and consisted on survival rate evaluation of sixteen selected plant species subjected to three distinct periods of irrigation and three different substrate mixtures [41]. Based on these results was selected one type of substrate, a lightweight composition with 60% organic and 40% inorganic components, specially developed for green roofs. In the wall were installed the species that showed a higher survival rate. On the top of the wall were installed the *Sedum* species having less irrigation needs and on the bottom part the *Thymus* species taking advantage of the vertical displacement of irrigation water by gravity (see Fig. 10).

During Period 2, after the installation of vegetation and substrate in Geogreen wall, emerged the need to irrigate the system to ensure that the substrate keeps the amount of moisture needed for

Fig. 9. Comparison of temperature variations between the reference wall and the Geogreen wall with plants and substrate (Photographs taken on October 8th 2013 at 13h53): a. Reference wall; c. Geogreen wall with plants and substrate; d. Temporary support structure; e. Irrigation system; f. Meteorological station.

Fig. 8. Comparison of temperature variations between the reference wall and the Geogreen wall (Photographs taken on August 1st 2013 at 12h08): a. Reference wall; b. Geogreen wall without plants and substrate; d. Temporary support structure; f. Meteorological station.

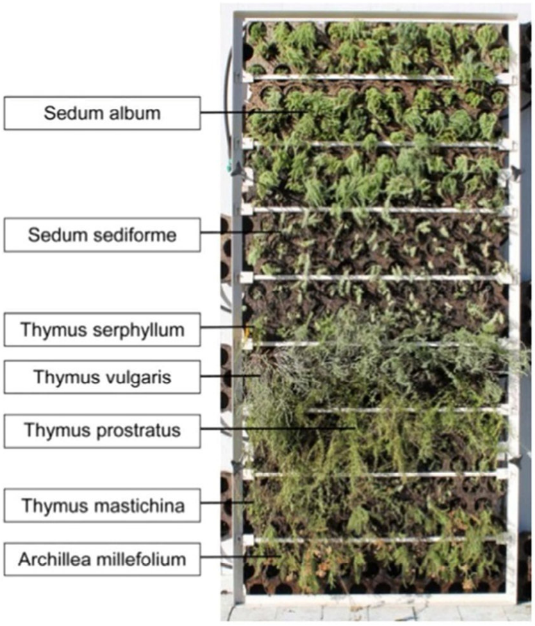

Fig. 10. Plant species installed in the tested Geogreen wall.

plants survival.

The Geogreen wall was irrigated in the 7th, 9th and 11th of October at the end of the afternoon, around 17:00 by a perforated tube installed under the substrate, which worked between 4 and 7 min until the modules were completely wet. In day 2 the air relative humidity was between 68% and 38%, achieving its minimum at 15:00. Therefore the Geogreen wall was irrigated during 4 min. However the variation of air relative humidity increased in day 4, which was between 74% and 30%, achieving its minimum at 15:30. Considering that the Geogreen wall was visibly dry in day 4 it led us to increase the irrigation to a 7 min period.

3.4. Weather analysis

For the purpose of this study three Periods were considered. Period 1 corresponds to a cooling season, with high exterior ambient temperatures (T_{ext}) reaching to 32.8 °C and a maximum global solar radiation of 894 W/m^2. Period 2 is a mild season with daily temperatures between 25.7 °C and 9.1 °C and a maximum global solar radiation of 692 W/m^2. Period 3 corresponds to a heating season with very low temperatures, mostly during the night, showing temperature variations between 15.2 °C and −1.2 °C.

Maximum global solar radiation obtained in the days of each period is quite constant. Nevertheless, drops can be justified by the presence of some cloudiness. When comparing the maximum global solar radiation (G) for each selected period, it can be noticed that it was reduced to less than half between Period 1 and 3, which must reflect significantly on solar gains of the exposed surfaces.

4. Analysis and discussion

This study comprises the comparative analysis of interior surface temperatures and heat fluxes between a bare wall, named as reference wall, and a wall covered with Geogreen modules in different setups, identified as Geogreen wall (Figs. 11 and 12). In a first setup (Period 1) the Geogreen wall includes only the Geogreen modules fitted into each other without any vegetation and substrate (see Fig. 8). In a second setup (Periods 2 and 3) the Geogreen wall includes the Geogreen modules filled with vegetation and substrate (see Fig. 9).

Geogreen wall, reached to lower maximum interior surface temperatures and higher minimum interior surface temperatures than the corresponding reference walls in all Periods (Fig. 13).

In fact, reference wall maintains high interior surface thermal amplitude ($\Delta T_s = T_{s\ max} - T_{s\ min}$) in all periods but the Geogreen wall had a significant reduction in the interior surface thermal amplitude between the analysed periods (Table 1). Interior surface thermal amplitude ($\Delta T_{s\ x}$) is obtained from the difference between the maximum daily interior surface temperature ($T_{s\ min}$) and the minimum daily interior surface temperature ($T_{s\ min}$).

From the analysis of reference wall heat fluxes ($\phi_{s\ ref}$) along all periods (see Fig. 14) it can be said that higher incoming heat fluxes were reached during Periods 1 and 2. The incoming and outgoing heat fluxes present the same behaviour in Periods 1 and 2 with higher thermal gains during the day and overnight thermal losses. However the main direction of heat flux is substantially changed in Period 3, in which the outgoing heat fluxes are superior to the incoming heat fluxes. These results show how reference wall is barely thermal insulated.

In Geogreen wall the incoming heat fluxes ($\phi_{s\ G}$) decrease significantly from Period 1 to Period 3. Yet, the outgoing $\phi_{s\ G}$ followed the opposite direction.

From the obtained results between Geogreen wall and reference wall in each Period, it can be said that thermal gains by conduction are reduced by 37% in Period 1 with the application of Geogreen elements and by 75% in Period 2, with application Geogreen elements filled with substrate and plants. In Period 3 the results are also positive revealing a reduction by 60% in maximum outgoing heat flux.

4.1. Effect of Geogreen modules

The comparison of results between reference wall and Geogreen wall during Period 1 allows understanding the effect of Geogreen modules based on their composition with a geopolymer base plate and the ICB upper plate with circular openings, without any vegetation and substrate in the openings (see Fig. 8).

From the results obtained in Period 1 it can be said that Geogreen modules provide additional thermal protection to temperature variations in the cooling season. The Geogreen wall reflects a drop in the average daily thermal amplitude up to 4.1 °C. It increases the minimum interior surface temperature up to 1.8 °C and reduces of the maximum interior surface temperature up to

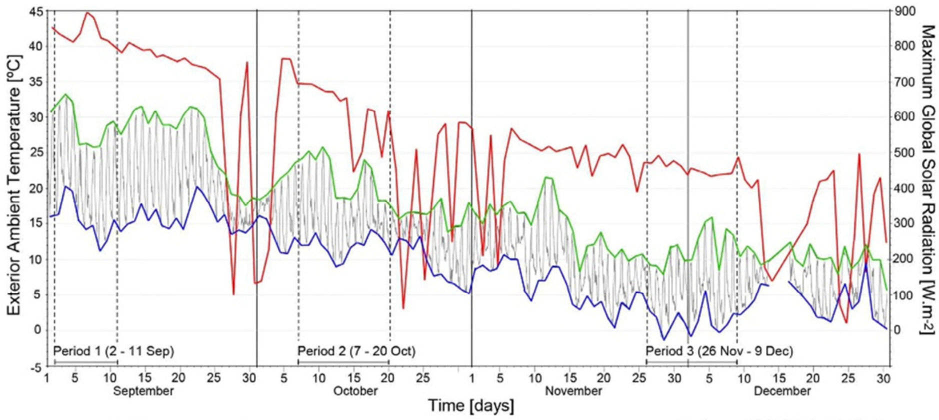

Fig. 11. Exterior ambient temperature and global solar radiation along the selected periods.

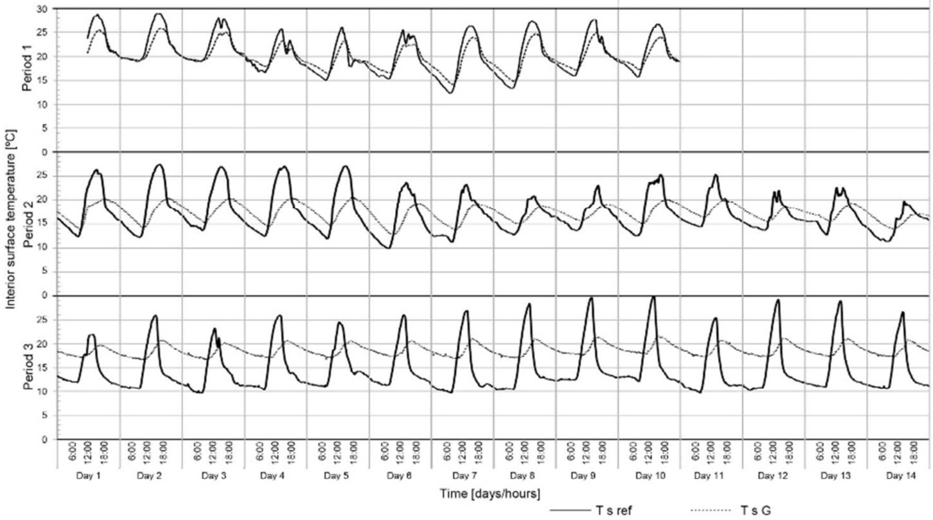

Fig. 12. Interior surface temperatures of reference wall ($T_{s\ ref}$) and Geogreen wall ($T_{s\ G}$) during Periods 1, 2 and 3.

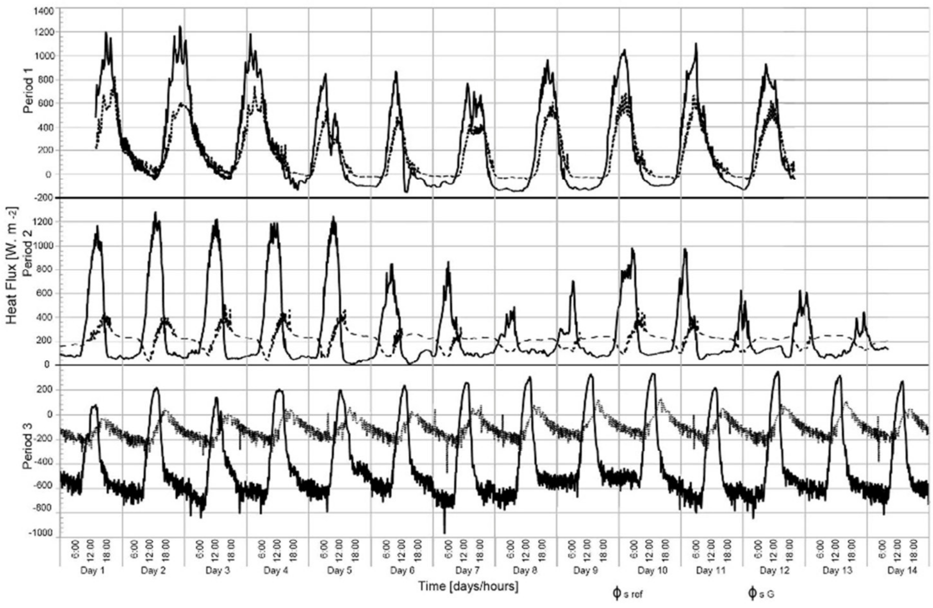

Fig. 13. Incoming/outgoing heat flux obtained in reference wall ($\phi_{s\ ref}$) and Geogreen wall ($\phi_{s\ G}$) during Periods 1, 2 and 3.

3 °C.

In Period 1 incoming heat fluxes occurred during the day in both walls, reaching to its maximum in the afternoons. The obtained results demonstrate how Geogreen elements by themselves have a positive impact on the wall thermal resistance.

4.2. Effect of vegetation and substrate

The evaluation of the effect of vegetation and substrate inserted in Geogreen modules openings is made in Periods 2 and 3 (see Fig. 9). In Period 2 the temperature difference between maximum temperatures of reference wall and Geogreen wall reached to 7 °C in the day with maximum solar radiation. Its impact is also evident in Period 3, when the climatic conditions where most unfavourable. During Period 3 the maximum temperature difference reached to 8.8 °C and the minimum temperature difference reached to −7.7 °C.

Geogreen system introduces attenuations in the interior surface temperatures both in Periods 2 and 3. It contributes to an effective reduction of maximum interior surface temperatures, which did not exceed 20.6 °C in Period 2. And it contributes to increase minimum interior surface temperatures, which values

Table 1
Maximum and minimum interior surface temperatures and thermal amplitude of reference wall ($T_{s\ ref}$) and Geogreen wall ($T_{s\ G}$) in the selected periods.

$T_{s\ ref}$ (°C)				ΔT_{ref} (°C)	$T_{s\ G}$ (°C)		ΔT_G (°C)
Days		Max.	Min.		Max.	Min.	
Period 1	02-09-2013	28.8	19.9	8.9	25.4	20	5.4
	03-09-2013	29	18.9	10.1	25.8	19.1	6.7
	04-09-2013	28.1	18.9	9.2	25	19.1	5.9
	05-09-2013	25.7	16.6	9.1	23.3	17.9	5.4
	06-09-2013	26.1	15	11.1	23.1	16.5	6.6
	07-09-2013	25.5	15.3	10.2	22.5	16.5	6
	08-09-2013	26.4	12.4	14	23.9	14.2	9.7
	09-09-2013	27.4	13.3	14.1	24.7	14.8	9.9
	10-09-2013	27.7	15.9	11.8	25	17.1	7.9
	11-09-2013	26.7	15.7	11	24	17.2	6.8
	Average	27.1	16.2	11.0	24.3	17.2	7.0
Period 2	07-10-2013	27.5	12.2	15.3	20.5	14.2	6.3
	08-10-2013	27	13.6	13.4	20.4	15.2	5.2
	09-10-2013	27.1	12.4	14.7	20.5	14.5	6
	10-10-2013	27.2	11.9	15.3	20.6	14.6	6
	11-10-2013	23.7	9.9	13.8	19.3	12.8	6.5
	12-10-2013	23.3	11.2	12.1	19.2	13.8	5.4
	13-10-2013	20.9	12.7	8.2	18.8	15	3.8
	14-10-2013	23.1	13.6	9.5	19.2	13.6	5.6
	15-10-2013	25.4	12.6	12.8	20.3	15.1	5.2
	16-10-2013	25.4	14.4	11	19.9	16.3	3.6
	17-10-2013	22.1	13.7	8.4	18.7	13.7	5
	18-10-2013	22.7	12.7	10	19.3	15.5	3.8
	19-10-2013	19.8	11.4	8.4	17.4	14	3.4
	20-10-2013	15.7	14.1	1.6	16.7	15.3	1.4
	Average	24.4	12.5	11.9	19.6	14.4	5.2
Period 3	26-11-2013	22	11.4	10.6	19.7	17.1	2.6
	27-11-2013	26	10.6	15.4	20.8	16.8	4
	28-11-2013	23.3	9.6	13.7	20.2	16.8	3.4
	29-11-2013	26	10.3	15.7	20.7	17.1	3.6
	30-11-2013	24.6	11	13.6	20.6	16.6	4
	01-12-2013	26.1	11.3	14.8	20.6	17.3	3.3
	02-12-2013	27	9.7	17.3	21.1	16.9	4.2
	03-12-2013	28.5	10.3	18.2	21	17	4
	04-12-2013	29.8	12.3	17.5	21.4	17.6	3.8
	05-12-2013	30.4	11.9	18.5	21.6	17.9	3.7
	06-12-2013	25.5	9.6	15,9	20.8	17.3	3.5
	07-12-2013	29.3	10.2	19.1	21.1	17.3	3.8
	08-12-2013	29	10.9	18.1	21.1	17.4	3.7
	09-12-2013	26.7	10.6	16.1	20.8	17.2	3.6
	Average	26.7	10.7	16.0	20.8	17.2	3.7

were above 12.8 °C in Period 2 and 16.6 °C in Period 3.

Through the analysis of the entire temperature range between reference wall and Geogreen wall it can be stated that Geogreen system has impact on thermal wave damping. In fact is in Period 3, that the thermal protection offered by Geogreen elements filled with vegetation and substrate becomes more evident.

The system contributes to decrease the average daily interior thermal amplitude (Average ΔT_{ref}−Average ΔT_G) up to 11.3 °C in Period 3. It is also noted that in Period 3, Geogreen wall interior surface temperatures get closer to comfort zone, despite low external temperatures and low global solar radiation.

Through the comparison of heat fluxes in reference wall and Geogreen wall, it can be noticed that the Geogreen system helps to mitigate and delay heat transfer in both directions.

When exterior ambient temperatures and solar radiation are high (during the day) Geogreen wall attenuates and delay energy flow into the interior, avoiding interior spaces to overheat. In fact during Period 2, Geogreen wall had 75% less thermal losses by conduction than reference wall. It is also important to note that while reference wall had mainly thermal gains by conduction during the day, Geogreen wall only had them during the night. This demonstrates how Geogreen wall increases the wall thermal mass. Considering its materials and composition, it has the ability to absorb a significant part of the heat coming from the outside along the day (mainly solar radiation and convection heat transfer with ambient air) and slowly release it into the interior overnight.

These results reflect the thermal contribution of Geogreen wall to avoid overheating. And demonstrate how the application of Geogreen wall can contribute to reduce cooling loads and consequently decrease buildings energy consumption.

In Period 3 temperature drop is mitigated by the application of Geogreen wall, which contributes to the reduction of thermal losses by conduction in 60%. Yet, the reduction of thermal gains and thermal losses in Geogreen wall demonstrates how the Geogreen system increases the wall thermal insulation.

Therefore it can be considered that the Geogreen wall with vegetation and substrate contributes to mitigate the heat fluxes peaks and to provide a thermal delay between the exterior and the interior and consequently affect positively the thermal response of the wall. Overall, Geogreen modules with vegetation and substrate improve the thermal response of the wall, allowing both higher thermal resistance and higher thermal mass than reference wall.

4.3. Phase 2

A second study was developed between February and March 2015 in order to replicate the walls and alternate their position in the outdoor test cell. During this period were determined the exterior and interior surface temperatures in both walls. At first the Geogreen wall was located in wall A (week 1) and then it was positioned in wall B (week 2) (Fig. 15).

As shown in Fig. 16, the exterior surface temperature difference between Geogreen wall and Reference wall is significant, reaching up to 15 °C. Higher values were obtained in days with higher solar radiation. The results demonstrate how the Geogreen elements have also the ability to reduce the wall exterior surface temperature during the day and increase it at night.

5. Conclusion

This study investigates the influence of a new modular green wall system on the thermal behaviour of building envelopes and its impact on their indoor environment in a Mediterranean climate. The modular system comprises water retaining geopolymeric base plate that slowly supplies water into the plants and an Expanded Cork Board (ICB) upper plate that reduce heat loss through the envelop during winter, aiming to create a sustainable system for green roofs and green walls.

Overall, the obtained results point out the effectiveness of Geogreen system when compared with bare wall under the same environmental conditions. The research focused on the comparison of the interior surface temperatures and heat flux between a Reference wall and the Geogreen wall in three different periods. From this study it can be concluded that for the evaluated periods, when compared to a reference wall, the studied system:

- Offers an additional thermal protection to temperature variations even without vegetation and substrate in its openings.
- Improves thermal comfort of indoor spaces by reducing the interior thermal amplitude of walls, decreasing and delaying walls heat flow between the interior and exterior.

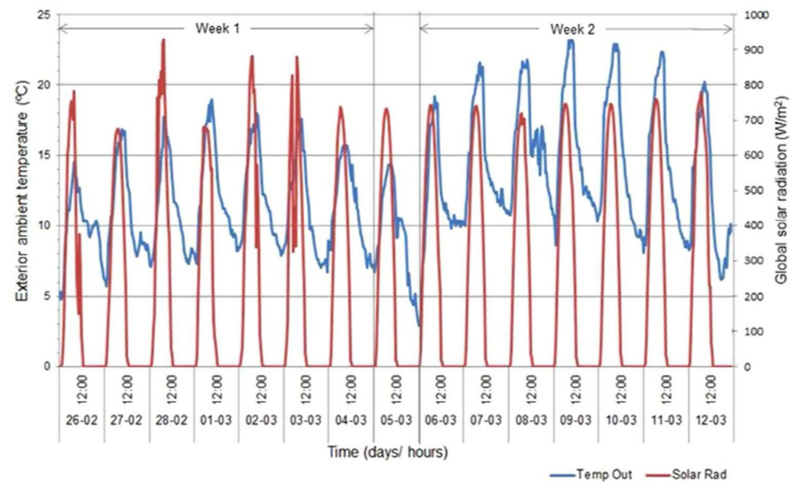

Fig. 14. Exterior ambient temperatures and global solar radiation during phase 2.

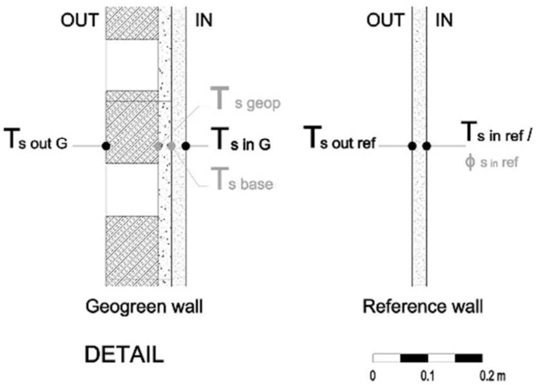

Fig. 15. Surface probes positioning in Geogreen wall.

– Introduces an increased attenuation of interior surface temperatures when applied with plants and substrate. Reducing maximum interior surface temperatures and increasing minimum interior surface temperatures up to 7 °C, during heating season.
– Has impact on the thermal wave damping. It contributes to decrease the average daily interior thermal amplitude (Average ΔT_{ref} – Average ΔT_G) in 11.3 °C, during heating season.
– Helps to mitigate heat transfer by increasing the thermal delay between the exterior and the interior.
– Reduces thermal gains by conduction in 75% in warmer days and thermal losses in 60%, during heating season.
– And contributes to reduce the exterior surface temperature up to 15 °C.

So, this solution can contribute to the improvement of buildings thermal performance in order to provide a better thermal comfort for buildings occupants.

Further results may comprise the analysis of Geogreen wall thermal behaviour during a cooling season, namely to determine

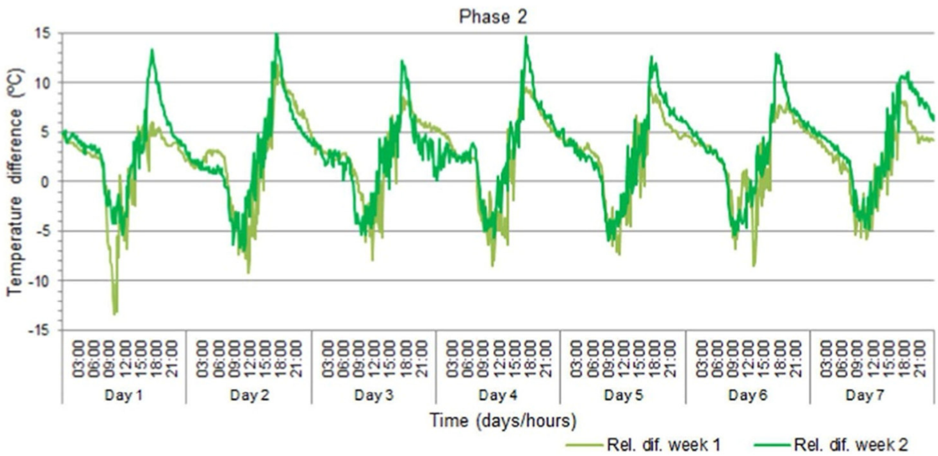

Fig. 16. Exterior surface temperature difference between Geogreen wall and Reference wall in Phase 2.

its potential as passive cooling system. And how it can contribute to reduce and time shift of the cooling load peaks avoiding oversized air conditioning systems, with higher energy consumption.

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Chapter 7

Acoustic Evaluation of a new modular system for green roofs and green walls

This chapter consists of the following article:

Acoustic Evaluation of a new modular system for green roofs and green walls.

Manso, M., Castro-Gomes, J.P., Marchacz, M., Górski, M., Dulak, L. Zuchowski, R.

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ACOUSTIC EVALUATION OF A NEW MODULAR SYSTEM FOR GREEN ROOFS AND GREEN WALLS

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Abstract
Environmental noise is a major problem that affects citizen's health and comfort mainly in densely populated urban areas. There are some ways to reduce environmental noise pollution through the use of materials with good acoustic insulation properties in buildings envelope. Recent studies have shown that green surfaces, e.g. in the form of green roofs and green walls, can contribute to decrease noise levels.
The aim of this research is to identify how factors such as substrate and plants, variety and height of plants, affect the sound absorption of a modular system for green surfaces in simulated conditions. The results show that introduction substrate (S2) can improve the weighted sound absorption coefficient in 15% and the addition of plants (S3) improves it 20% more. However, if a variety of smaller and higher plants is used (S4) the weighted sound absorption coefficient (α_W) can reach to 0.80 and an absorption class B can be obtained.

Streszczenie
Hałas środowiskowy jest jednym z ważniejszych problemów wpływających na zdrowie i komfort życia mieszkańców miast, szczególnie na terenach gęsto zaludnionych.
Jest kilka sposobów ograniczania zanieczyszczenia hałasem środowiskowym poprzez stosowanie materiałów elewacyjnych o dobrych parametrach akustycznych. Wiele opracowań pokazuje, iż powierzchnie zielone, np. w formie zielonych dachów czy zielonych ścian, mogą przyczyniać się do obniżenia poziomu hałasu.
Przedmiotem opracowania jest wskazanie jak czynniki takie jak podłoże, roślinność oraz zróżnicowanie wysokości roślin wpływa na pochłanianie dźwięku przez modułowy system powierzchni zielonych w warunkach laboratoryjnych. Wyniki wskazują, iż wypełnienie podłożem (S2) może poprawić jednoliczbowy wskaźnik pochłaniania dźwięku (α_W) o 15%. Udział roślinności (S3) poprawia ten parametr o ponad 20%. W przypadku wariantu zawierającego mniejszą i większą roślinność (S4) jednoliczbowy wskaźnik pochłaniania dźwięku (α_W) może osiągać wartości do 0.80 oraz klasę pochłaniania B.

Keywords: **Acoustic; Green roofs; Green walls; Modular system; Sound absorption coefficient.**

1. INTRODUCTION

Environmental noise is a major environmental problem that affects citizen's health and comfort mainly in densely populated urban areas [1-4]. The EU Directive 2002/49/EC defines the environmental noise as the unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic and from sites of industrial activity [5].

There are different methods of acoustic protection, such as noise barriers or special construction materials for roads [6-10]. However, these are often insufficient solutions.

One way to partially reduce noise levels in the environment is the use of appropriate solutions and materials in buildings construction. Dense urban areas often include highly reflective and low sound absorption construction materials that contribute to increase sound levels. However, materials with good absorbing performance can positively affect the acoustics of surrounding environment [11-12].

There is now a number of new approaches for the implementation of nature-based solutions including integrating living systems with built systems. Green roofs and green walls are seen as examples of these nature based solutions. These methods are centred on the importance of greening cities to reduce pollution, noise and improve health. And develop prevention and mitigation strategies that help reducing the impact of noise on society, focusing particularly on urban settings and areas in the vicinity of motorways [13].

Often good acoustic parameters are characteristic for materials containing vegetation. The integration of vegetation in the urban environment, either in the form of green roofs or green walls, brings many environmental benefits while helping to improve urban design [14] and to create a more sustainable urban environment [15-17].

In fact, green roofs and green walls contribute, among other benefits, to: improve human health and well-being, enhance biodiversity, mitigate the urban heat island effect [18], reduce flood and drought risk while helping in the use and distribution of rainwater [19], store carbon [20], protect surfaces from direct sunlight and contribute to the thermal performance of buildings [21]. As a matter of fact, green roofs increase the thermal mass and thus significantly improve the dynamic thermal properties of the flat roof. As a consequence, they improve the microclimate parameters of rooms under the flat roof [22].

Green roofs and green walls can be also a desired solution where green areas are scarce [14, 23] and citizens are exposed to high levels of environmental noise. Actually, green roofs and green walls can have an impact on long-distance noise propagation in the urban environment [24-25] resulting most likely from road traffic noise [26]. Recent investments in new systems led to the assessment of their acoustic characteristics [27, 28]. It was proven that green roofs can reduce the surrounding sound by providing increased acoustic insulation to buildings envelope and absorbing sound waves diffracting over roofs [29]. The acoustic contribution of green roofs and green walls depends not only of the presence of the vegetation [30,31] but also of the system, considering its mass, impenetrability and structural insulation of the support [32]. Several studies have also proven that the types of vegetation [33], the presence of substrate and vegetation cover percentage [27] have also an influence in the acoustic contribution of these systems.

This paper aims to analyse the influence of factors such as substrate and plants, variety and height of plants and how these affect the sound absorption of a modular system (GEOGREEN) for green surfaces in simulated conditions. For this purpose, an experimental study is prepared based on four different setups tested in a reverberation chamber under similar conditions. Results refer to a comparison of sound absorption coefficients α_S versus frequency between setups. These results are also compared with the sound absorption coefficient of a conventional acoustic insulation material and with the results obtained by similar studies.

2. CHARACTERISTICS OF THE MODULAR SYSTEM FOR VEGETATED SURFACES

2.1. Composition

GEOGREEN system is based on modular elements locked together to make a continuous vegetated surface. The system can be installed vertically, horizontally or in sloped surfaces. It can be set in the envelope or interior spaces of new and retrofitted buildings. This way it accounts the design particularities of each surface for creating green roofs or green walls. The system has a simple installation process allowing manual application and individual insertion and substitution of each module [34]. The modular system allows the support of plants and substrate using waste recycled industrial materials and expanded cork.

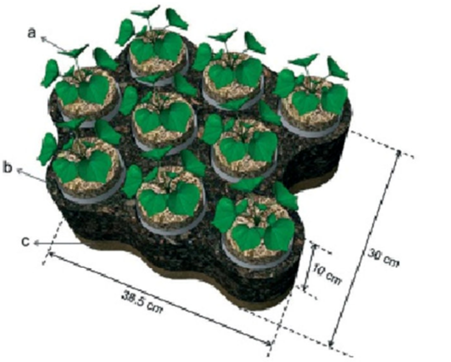

Figure 1.
GEOGREEN modular element design with plants and substrate: a. Adapted plant species; b. Upper plate in expanded cork board; c. Base plate of lightweight geopolymeric binder

Each module has 38.5 cm length, 30 cm width and 10 cm thickness, as presented in Figure 1. It consists of two layers of different materials. The bottom layer is a rigid base plate of 2 cm thickness made of mining waste-based geopolymeric lightweight binder incorporating granulated expanded cork [23]. It is produced by a curing period of 7 days at 60°C temperature in a proper mould. After curing, it shows low water absorption, low-density and good mechanical strength [35]. The upper layer consists of expanded cork board plate (ICB) obtained by CNC-cut with a bulk density in the range of 140-150 kg/m^3. The average total weight of each module including substrate and inserted plants is about 5,650 kg (divide as follows: 2.750 kg for base plate, 650 g for upper layer and 2.250 kg for soil and plants).

2.2. Thermal performance preliminary results

According to a study based on real climate tests performed in a dry mesomediterranean climate (dry and hot season, cold temperate season, large thermal gap between summer and winter seasons) the GEOGREEN system presents a good thermal performance. It attenuates the minimum and maximum interior surface temperatures up to 7°C; mitigates heat transfer, reducing the maximum incoming heat flux by 75% and maximum outgoing heat flux by 60%. Therefore it enhances the thermal insulation of external walls while increasing thermal delay between the exterior and the interior [36].

3. SOUND ABSORPTION TESTING

3.1. Modular system testing setups

The aim of this research is to identify how factors such as substrate and plants, variety and height of plants, affect sound absorption in simulated conditions. For this purpose, four different setups were prepared to be tested (see Table 1). The first consists of testing the modular elements without substrate and plants (S1). The second one includes the same modular elements containing substrate (S2). A third test was performed using the modular elements with substrate and plants with an average height of 7-8 cm (S3) (see Fig. 3). The latest has the same elements as setup S3, however, 10% of the plants with 7-8 cm high were replaced by plants with an average height of 25-30 cm (S4) (see Fig. 3). Additionally, the research aimed to establish a sound absorption comparison between the modular system and a mineral wool sample, set as a reference material (REF).

Acoustic properties testing for setups S1, S2, S3 and S4 were carried out using a surface of 25 GEOGREEN modular elements with a total area of 2.99 m^2. Mineral wool reference sample (REF) was assembled with 6 mineral wool plates with 5 cm thickness each in two layers creating a total area of 2.76 m^2. In all cases total area was calculated as a sum of upper area and lateral allowance.

Regarding setup S2, the holes in each module were filled with a conventional green roof substrate until about two thirds of its volume. This corresponds to the situation when the modules are filled with substrate but the plants are not yet grown.

The tested modular system samples positioning in the reverberation chamber is shown in Figure 2.

Table 1.
Sound absorption testing setups

Setup	Characteristics	Sample area (m^2)	Plants 7-8 cm	Plants 25-30 cm
S1	Modular elements (geopolymeric base plate + expanded cork board upper plate)	2.99	-	-
S2	Modular elements (setup S1) with substrate	2.99	-	-
S3	Setup S2 and plants (≈7-8 cm height)	2.99	100%	-
S4	Setup S2 and plants (90% ≈7-8 cm height and 10% ≈30 cm height)	2.99	90%	10%
REF	Mineral wool plates (2 layers, h=5cm each)	2.76	-	-

Figure 2.
Sound absorption testing in reverberation chamber: S1 (left); S4 (right)

Figure 3.
Sound absorption tests of modular elements with plants: S3 (left); S4 (right)

In setup S3 and S4 a diversity of 7 plant species were used, namely: *Nepeta* (Walker's Law), *Sedum cyaneum* (Stonecrop), *Sedum sediforme, Sedum sieboldii, Serum kamtchaticum, Sedum variegatum, Sedum spurium purpureum, Sedum reflexum, Serum Acre*.

Prior to sound testing the modular system samples were seasoned for a period of one week in similar climatic conditions (temperature and relative humidity) to the conditions inside the reverberation chamber.

3.2. Acoustic reverberation chamber characteristics

To determine the acoustic quality of sound absorbing products there are two popular ways among the standardized methods. Measurement of reverberation time based on the S.C. Sabin's formula in a reverberation chamber in accordance with the methodology included in ISO 354:2003 [37]. And measurement method of standing wave in impedance tube according to ISO 10534-1:1996 [38]. For this experiment the method of measuring the reverberation in a chamber was chosen.

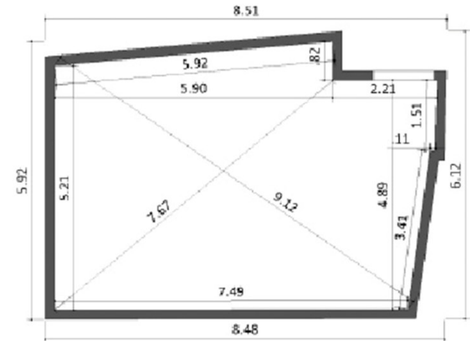

Figure 4.
Reverberation chamber floorplan

An experimental study for assessment of the sound absorption coefficient of the modular system under

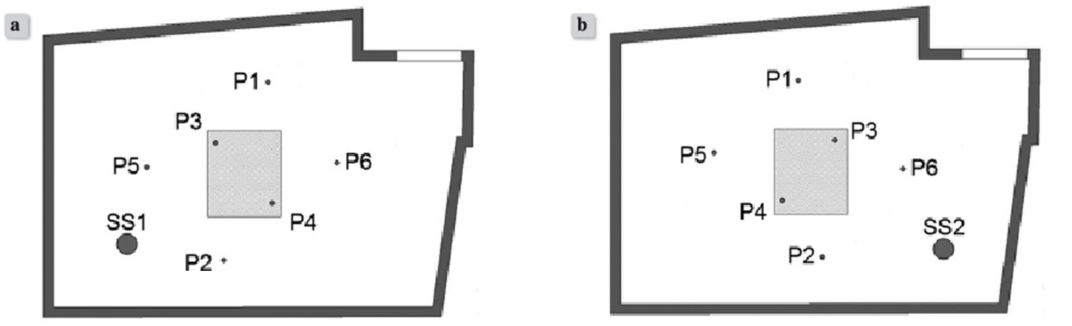

Figure 5.
Reverberation chamber scheme. Microphones positioning (P1 to P6); a) First sound source setting (SS1); b) Second sound source setting (SS2)

different conditions was developed in a reverberation chamber with a volume of 192.7 m^3 (Figure 4). The reverberation chamber follows the requirements contained in the standard ISO 354:2003 [37]. Its shape follows also the following condition:

$$I_{max} < 1.9\ V^{1/3} \qquad (1)$$

where V is the volume of the chamber, I_{max} is the length of longest straight line in interior of the chamber. The materials used for finishes on walls, ceiling, and floors have very good scattering parameters. For proper diffusion of sound field inside of the chamber, nine scattering elements (partially visible on the Figure 2 as hanging boards) were used.

Table 2.
Instrumentation for sound absorption measurements

Speaker	Sound source with a spherical radiation pattern	
Amplifier	Acoustic generator of pink noise	
Sound level meters	SVAN 958, no. 15810	
Microphones 1/2"	SV22 type, no. 4013121 and no. 0413114	
Microphone preamplifiers 1/2"	SV12L type, no. 24899 and no. 24898	Svantek
Sound calibrator	SV03A type, no. 2524	
Software	Software SvanPC Version 1.8c	
Temperature and humidity meter	Lufft T200	

3.3. Instrumentation setup and sound absorption determination

According to ISO 354:2003 [37] studies can be carried out using the method of intermittent noise or impulse response integration method. The method of intermittent noise was chosen for the presented study. Table 2 summarises the instrumentation used to measure the sound absorption in the reverberation room. This includes a speaker with a spherical radiation pattern, a generator of pink noise and an amplifier to make the transmitting sound testing tracks, four channel sound level meters, used as receivers of the testing tracks, and two microphone preamplifiers as sound calibrators. All these devices fulfil the EN 61672-1:2014 standard [39].

Figure 5 schematically present the instrumentation and different setups adopted to carry the acoustic tests for assessing the sound absorption coefficient of different setups.

The samples were positioned at the centre of the chamber and the instrumentation setup positioning varies as shown in Figure 5.

The reverberation times were measured using a generator of pink noise (turned on for 12 seconds as it was considered the minimum time of sound propagation inside the chamber, to be identical or longer than the reverberation time), two speakers (SS1 and SS2) and six microphones placed on rotary columns in two starting positions (marked as a P1 to P6), 1.5m above the samples (see Fig. 5). Temperature and humidity were checked after each measurement.

The sound absorption coefficient (α_S) for each third octave band, between 0.100 kHz and 5 kHz, was determined according to UNE-EN ISO 354 standards. It results from the quotient of equivalent sound absorbing area of the measuring sample (A_T) and the sample area (S):

Table 3.
Summary of sound absorption testing results

Setup	Characteristics	α_w coefficient	Absorption class
S1	Modular elements (geopolymeric base plate + expanded cork board upper plate)	0.4 (H)	D
S2	Modular elements (setup S1) with substrate	0.55 (M H)	D
S3	Setup S2 and plants (≈7-8 cm height)	0.75 (H)	C
S4	Setup S2 and plants (90% ≈7-8 cm height and 10% ≈30 cm height)	0.8	B
REF	Mineral wool plates (2 layers, h=5cm each)	1.0	A

$$\alpha_S = \frac{A_T}{S} \qquad (2)$$

$$A_T = 55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1) \qquad (3)$$

More necessary information is included in ISO 9613-1: 2010 standard [40]. The practical sound absorption coefficient α_{pi} for each octave band was also determined according to the equation:

$$\alpha_{pi} = \frac{\alpha_{i1}+\alpha_{i2}+\alpha_{i3}}{3} \qquad (4)$$

The conversion of the frequency-dependent sound absorption coefficient to one number (α_w) is allowed by EN ISO 11654:1997 [41]. According to this norm the weighted sound absorption coefficient α_w is a mark of sound quality of acoustic materials.

4. RESULTS AND DISCUSSION

The sound absorption coefficient α_w and absorption class of each testing setup and the reference material are summarized in Table 3. According to ISO 11654:1997 the studied modular system for green roofs and green walls can be classified as absorbent, considering that α_w is higher than 0.15. While setups S1 and S2 are included in the absorption class D, setup S4 and S3 are included in the absorption class B and C, respectively. It is also relevant to mention that a shape indicator was added to α_w of setups S1, S2 and S3. Shape indicators inform that in some ranges the sound absorption coefficient is higher than values of shifted reference curve. In setups S1 and S3 the shape indicator H informs that the practical sound absorption coefficient α_p has exceeded the values of shifted reference curve by 0.25 in the frequency range of 2000 to 4000Hz. In setup S2 the

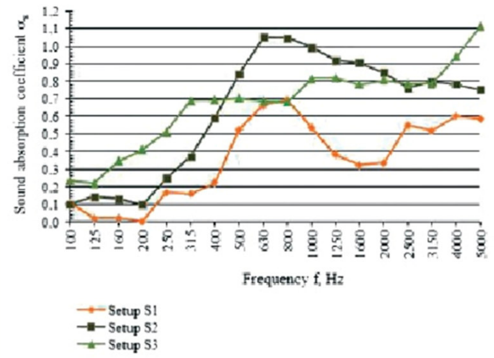

Figure 6.
Sound absorption coefficients α_S in frequency function for setup S1, S2 and S3

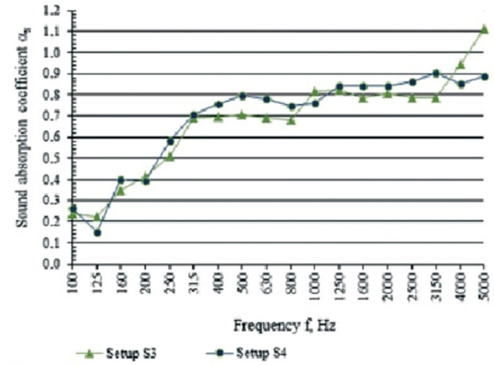

Figure 7.
Sound absorption coefficients α_S in frequency function for setups S3 and S4

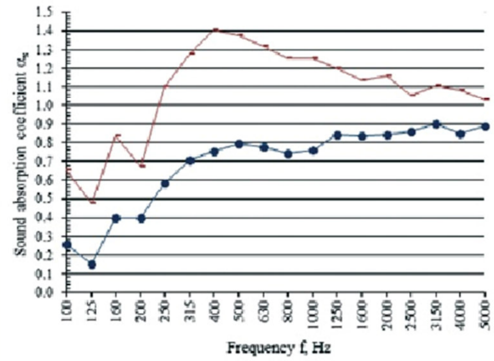

Figure 8.
Sound absorption coefficients α_S in frequency function for setup S4 and REF

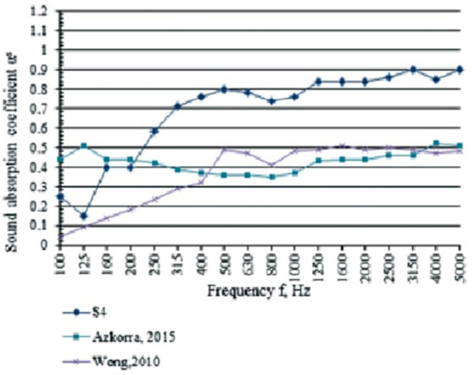

Figure 9.
Comparison of sound absorption coefficients α_s with other authors

shape indicators M and H show that the practical sound absorption coefficient α_p has exceeded the values of shifted reference curve by 0.25 in the frequency range of 500 to 1000 Hz and 2000 to 4000Hz.

4.1. The influence of substrate and plants in sound absorption

The sound absorption coefficients α_s versus frequency for setup S1, S2 and S3 are presented in Figure 6.

The GEOGREEN modular elements on their own, without any substrate and plants (setup S1) show higher values of sound absorption coefficient only in the frequency range of 630-800 Hz. In the other frequencies, either lower or higher, the sound absorption values are significantly reduced. However, its sound absorption is quite promising when compared to other cladding materials like brick, plaster or tiles, as Azkorra et al. has demonstrated [28]. It may result from the fact that the GEOGREEN system has a non-uniform top layer of expanded cork board, a highly porous material, which allows acoustic waves to be absorbed.

In setup S2 the GEOGREEN modules were partially filled with green roof substrate. This setup (S2) shows improved results of the absolute absorption coefficient values along all frequencies, when compared with S1. This demonstrates the absorbing capacities of the substrate. The results show also a smoother curve than S1 along all frequencies. However, in a similar way, the greatest values of the absorption coefficient for setup S2 were obtained for the frequency range of 630-800 Hz, reaching in this case to values higher than 1.0 (maybe due to the sample area). Although the absorption parameters are higher than in S1, these are still decreasing from 630 Hz to 2500 Hz, like in setup S1. In relation to lower tones little improvement was achieved in S2 when compared with S1. In fact, the sound absorption coefficient α_w increased by 37% with the introduction of substrate in the modular elements, but setup S2 still remains in the absorption class D.

Finally, the results obtained for setup S3 (with plants inserted in the GEOGREEN modules) show a considerable improvement in the absorption parameters. The obtained result of a single number absorption coefficient α_w allows classifying the sample to the absorption class C. Besides, the insertion of plants indicates a significant improvement of the absorption properties in lower frequencies, when compared with the other two setups (S1 and S2).

4.2. The influence of plants variety and size in sound absorption

The comparison of results obtained in setup S3 and S4 (where 10% of 7-8 cm high plants was replaced by Sedum spectabile – Star Dust plants with approximately 30 cm high) are presented in Figure 7.

According to the results setup S4 can be classified as class B, the second highest absorption class. This indicates the acoustic potential for sound absorption of the tested setup. Setup S4, when compared to S3, shows a slight improvement of the sound absorption coefficient α_s in almost all frequencies. At the same time, the course of curve α_s for S4 is also smoother than for S3.

Although sound absorption values are similar in setups S3 and S4, it is known that vegetation development, shape and size interfere with the acoustical properties of the surface and sound absorption can increase along with vegetation density [27].

4.3. GEOGREEN potential as sound insulator

The results obtained in setups S1 to S4 were compared to a mineral wool sample (REF). Figure 8 compares the sound absorption coefficient versus frequency between setup 4 and REF. Mineral wool is known as an acoustic insulation material commonly used in construction sector to insulate buildings envelope, namely roofs and walls. This material has very good absorbing properties, obtaining a classification A as the best acoustic absorption category.

In this case REF α_w turned out to be only 20% better than S4, which indicates that S4 has potential good absorption properties. Assuming the course of an absorption curve α_s for REF, as reference, it can be noted that the general course of the absorption characteristics for sample S4 is similar to well-absorbing materials.

4.4. GEOGREEN comparison with other similar studies

Setup S4 is compared in Figure 9 with the results obtained by Wong et al. [27] and Azkorra et al. [28]. From this comparison it can be noticed that S4 is more effective than the others in higher frequencies reaching to a sound absorption coefficient of 0.8 at 500 Hz. In lower frequencies, less than 200Hz, S4 was not as sound insulator as the green wall tested by Azkorra et al.

5. CONCLUSIONS

In general, the studies for assessing the sound absorption of GEOGREEN modular system have shown it has good sound insulation characteristics, obtaining a classification as absorbent material in all setups.

The first setup, including the modules on their own (S1) obtained the lowest sound absorption coefficient (0.4). However, its results are quite promising when compared to other cladding materials like brick, plaster or tiles [28]. This may result from the fact that the GEOGREEN system has a non-uniform top layer of expanded cork board, a highly porous material, which allows acoustic waves to be absorbed.

Setup S2 demonstrates how the insertion of a low weight substrate can improve the weighted sound absorption coefficient of this system in 15%.

The impact of plants is also significant on the absorbing parameters of different tested setups. The presence of vegetation improves the parameters of sound absorption by one or even two classes. In these experiments, an improvement of 20% of weighted sound absorption coefficient (α_w) was achieved by setup S3, when compared to setup S2.

The application of an increased share of higher plants may be particularly promising in the potential of sound absorption. In this study replacing 10% of plants with 7-8 cm high by plants with 25-30cm high (S4) resulted in an improvement of 5% of its weighted sound absorption coefficient (α_w), which increased from 0.75 to 0.80. On the other hand, the variety of plants showed influence also in the absorption class, which reached a class B.

Through the comparison with other tested systems, it can be noticed that the GEOGREEN system with a variety of plants (S4) is more effective on sound absorption than the systems tested by Wong et al. [27] and Azkorra et al. [28], especially on higher frequencies, reaching to a sound absorption coefficient of 0.8 at 500 Hz.

The present study shows that the GEOGREEN system has good sound absorption properties. However, its contribution can still be improved based on the design and plants used, which can bring to new ways of further development and research directions.

Other studies have also demonstrated the noise reduction potential of green walls [27, 28, 42] and green roofs [29]. Therefore, further research can be performed to identify the actual contribution of this system to noise reduction in adjacent rooms.

Real case examples with the application of GEOGREEN elements in the external envelope of buildings. These would allow to, evaluate its performance in real conditions, considering the growth of different types of vegetation along the years.

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Chapter 8

Life Cycle Analysis of a new modular greening system

This chapter consists of the following article:

Life Cycle Analysis of a new modular greening system

Manso, M., Castro-Gomes, Paulo, B., J.P., Bentes, I., Teixeira, C.A.

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Life cycle analysis of a new modular greening system

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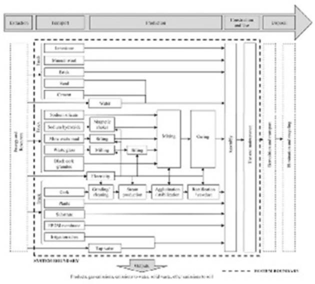
HIGHLIGHTS

- This study presents the LCA study of a new green wall and green roof system.
- Its support represents 96% of the total environmental burden in Global Warming.
- The alkali activated precast slab curing process has the highest impact.
- Curing process changes allowed reducing 74% the overall GWP.
- The comparison with other cladding systems revealed lower environmental impacts

GRAPHICAL ABSTRACT



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ABSTRACT

The construction and use of buildings represent about half of the extracted materials and energy consumption, and around one third of the water consumption and waste produced in the European Union. Therefore it is becoming more important to use sustainable materials that reduce the environmental impacts of construction, by conserving and using resources more efficiently.

Green walls can be used as a sustainable strategy to reduce the environmental impact of buildings. The aim of this study is to evaluate the environmental impact of a new modular system for green roofs and green walls (Geogreen) which uses waste and sustainable materials in its composition. A life cycle analysis (LCA) is used to evaluate the long term environmental benefits of this system. The life cycle analysis (LCA) is carried according to ISO 14040/44 using GaBi software and CML 2001 impact category indicators. The adopted functional unit is the square meter of each material required to assemble the Geogreen system. This study also compares the environmental performance of the Geogreen system with other living wall systems and other cladding materials using data from the literature.

This LCA study of the Geogreen system became relevant to identify a curing process with a major impact on GWP due to the energy consumed in this process. A change on this process allowed reducing 74% of the overall GWP. After this change it can be noticed that the Geogreen System presents one of the lowest environmental burden when compared to other construction systems.

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1. Introduction

1.1. Background

The construction and use of buildings represent about half of the extracted materials and energy consumption, and around one third of the water consumption (Matos et al., 2013) and waste produced in the European Union (E. Comission, 2014). These result from different stages of a building life cycle like materials production, building construction, use, renovation and building waste management. To improve the efficient use of resources it is becoming more important the selection of suitable materials and resources (energy (Chastas et al., 2017) and water use (Meng et al., 2014) in different building stages) to reduce the environmental impacts of buildings. Materials selection can be based on using raw materials from local sources, materials with low carbon emissions (Chen et al., 2011) and low embodied energy (Han et al., 2013) or materials with potential to be recycled or reused.

To overcome the increasing concern of resources depletion and to address environmental considerations, life cycle assessment (LCA) can be used to help with decision making (Khasreen et al., 2009) in order to improve sustainability in construction industry (Ortiz et al., 2009; Teixeira et al., 2014). LCA can also help to identify what materials or processes have more environmental impact and how materials and techniques can become friendlier to the environment.

Green walls and green roofs can be used as a sustainable strategy to reduce the environmental impact (Li and Yeung, 2014) of buildings. In fact, green areas are becoming scarce in densely populated cities. Therefore, these systems can be used as a strategy to integrate vegetation in the urban environment without land occupation (Virtudes and Manso, 2011). They are also mentioned in the Horizon 2020 Final Report "Nature Based Solutions and Re-Naturing Cities" (E. Commission, 2015) as a potential strategy of urban rehabilitation (Virtudes and Manso, 2016). Several studies have proven that green walls and green roofs have the potential to reduce air temperature in urban areas (Alexandri and Jones, 2008; Klein and Coffman, 2015), decrease flood risk and water runoff (Speak et al., 2013; Razzaghmanesh and Beecham, 2014) and air pollution (Rahman et al., 2011; Bruse et al., 1999; Rowe, 2011), increase biodiversity (Weiler and Scholz-Barth, 2009; Francis and Lorimer, 2011; Lundholm, 2006), encourage the fruition of urban areas (Virtudes and Manso, 2012) and improve quality of life (Virtudes and Manso, 2012). Greening solutions have also not only the capacity to improve buildings aesthetics but also contribute to improve buildings envelope and indoor conditions, acoustically (Ismail, 2013; Wong et al., 2010; Manso et al., 2017; D'Alessandro et al., 2015) and thermally (Alexandri and Jones, 2008; Castleton et al., 2010), while reducing energy demand for heating and cooling in buildings (Bass, 2007; Yoshimi and Altan, 2011; Pérez et al., 2014).

There are different types of green walls. Most systems can be integrated into two main categories, green facades and living walls. Green facades are simpler solutions, with less material input, use climbing plants that grow along the wall. Most recent concepts of green walls are called living wall systems (LWS). These include materials and technology to support a wider variety of plants, creating a uniform growth along the surface (Manso and Castro-Gomes, 2015).

Green roofs can be classified as intensive, semi-intensive or extensive. Intensive green roofs include a thicker layer of substrate which allows the integration of grass, shrubs and small trees. These systems require regular maintenance and irrigation (Peck et al., 1999). Semi-intensive green roofs have intermediate thickness, allowing the integration of a large number of plant species than extensive solutions and minimizing the maintenance and watering needs (Dunnett and Kingsbury, 2010; Newton et al., 2007). Extensive green roofs are lighter and have a thin layer of substrate which limits the type of plants included. They are frequently used to improve the conditions of non-accessible roofs, without overloading the building structure (Peck et al., 1999). Extensive green roofs have been evolving into simpler solutions, allowing the creation of vegetation covers in a shorter period of time using pre-planted mats or modular elements.

The object of this study is a new modular system for green roofs and green walls hereinafter referred to as "Geogreen". It has an innovative design and buildability, integrating simultaneously the characteristics of a modular extensive green roof and the properties of a modular living wall system. The design concept of a new modular system (Geogreen) for vegetated surfaces was developed to create more sustainable green roofs and green walls. This modular system results from the incorporating industrial waste materials and industrial sub-products into a construction system with added value. This system not only contributes to improve the aesthetic of buildings, as other greening solutions, but also improves the thermal comfort (Manso and Castro-Gomes, 2016) and acoustic conditions (Manso et al., 2017) of buildings envelope.

This study aims to demonstrate how the integration of sustainability strategies (e.g. use of recycled materials, reduction of embodied energy, industrial waste reuse) into the design of a solution for green roofs and green walls can contribute to a lower environmental impact and therefore make green roofs and green walls more competitive cladding solutions. More specifically, this study evaluates the environmental impact of an innovative greening solution (Geogreen). A life cycle analysis (LCA) is used to evaluate which materials and processes of the Geogreen system have greater environmental burden and determine how these impacts can be minimized. These results were also compared with other publications on life cycle analysis of green wall systems, green roof systems, other claddings and innovative composite solutions for external walls.

1.2. System description

Geogreen is a modular system of prefabricated elements with vegetation, suitable for new buildings and retrofitting and for the rehabilitation of existing buildings. This solution is based on the development of a modular living wall system (LWS) which incorporates industrial waste materials and industrial sub-products.

Each module of Geogreen system consists of a bottom layer of alkali activated precast slab and a top layer of expanded black cork board (Fig. 1). The modules were designed to allow its adaptation to different supports, and obtain a continuous and uniform layer of vegetation. The system can be applied manually and each module can be easily removed for maintenance purposes. The materials and plants used in the system aim to minimize the irrigation needs (Savi et al., 2016; Razzaghmanesh et al., 2014), to improve buildings thermal behaviour (Manso and Castro-Gomes, 2016) and their acoustic conditions (Manso et al., 2017).

Several studies have demonstrated that mineral wastes can be used as precursor materials for alkali-activated binders. Panasqueira tin tungsten mine, located in Portugal, is one of the largest tungsten mines in the world. It is an active industry that operates since 1890's. From the tungsten extraction process result two types of mine waste, coarse aggregates derived from rock blasting and waste mud conveyed by pipelines into lagoons, amounting to several tonnes of deposited material every year (Torgal et al., 2007). In fact recent research shows that mine waste mud from Panasqueira mines are rich in silica and alumina and show good reactivity with alkaline activators and other sources of silica (Centeio, 2011). Therefore the favourable mineralogical composition of mining waste for alkali activation combined with its continuously large production makes it an attractive and environmentally friendly feedstock for alkali activation binders (Kastiukas et al., 2017). Recent studies demonstrate that these alkali activated binders show good compressive strength and durability performance regarding abrasion and acid resistance (Castro-Gomes et al., 2010). Besides adding value to mine waste, the activation process, when complete, allows to encapsulate the arsenic and other heavy metals present in the mine waste mud, preventing its leaching to the environment (Castro-Gomes et al., 2010).

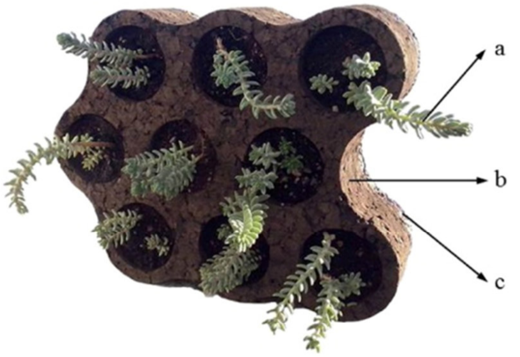

Fig. 1. Geogreen modular system design with plants and substrate. a. Adapted plant species; b. Upper layer in insulation cork board (ICB); c. Base layer in alkali-activated binder.

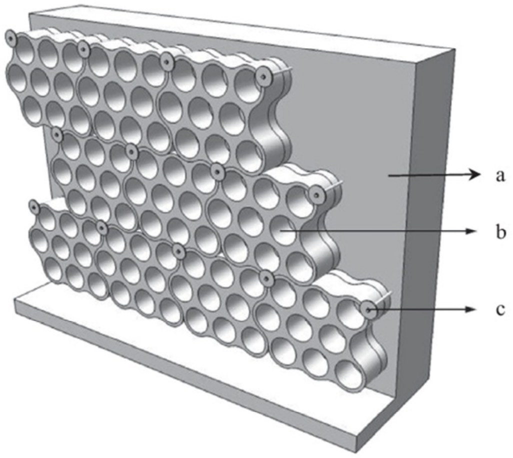

Fig. 3. Geogreen modules in vertical position with interlocking system. a. Bare wall; b. Geogreen modules (empty of soil and plants); c. Support screws and plates.

The alkali activated precast slab used in this system is obtained from the mixture of two industrial wastes used as precursors, mine waste mud from Panasqueira mine and milled glass. Milled glass is used to increase the amount of amorphous material in the mixture (Kastiukas et al., 2017). The binary blend is activated using a composite activator based on a mixture of sodium silicate and sodium hydroxide. Expanded black cork granules are also added to the mixture. They are a light weight aggregate which result from the crushing of waste expanded black cork agglomerate. In the alkali activated mixture they are used to reduce the binder density and increase its water absorption. The mixture is casted into a plastic mold and subject to a curing process in a ventilated oven at 60 °C during 7 days. The obtained mixture combines water absorption and water retention properties, low density and good mechanical strength.

The expanded black cork board is obtained from waste cork, a natural raw material which is extracted from the pruning of small branches of cork oaks. The production process of this material does not involve the use of chemicals or glues. The expansion and agglutination of cork granules is done by the action of water vapour. This process is free of any synthetic agent. It is presented by industry as a natural and sustainable material of low density and thermal and acoustic resistance. In this specific application it was also relevant that this material has enough mechanical resistance to support the vegetation. The expanded black cork board is entirely recyclable. Any waste material resulting from the rectification and cutting process can be crushed to create expanded black cork granules, such as those used in the alkali activated mixture.

After the production of both layers, the alkali activated precast slab is bonded to the expanded black cork board using neoprene glue.

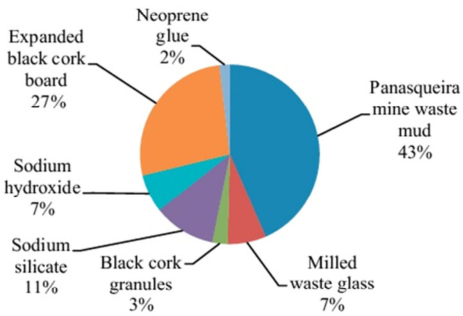

Fig. 2. Geogreen module materials weight percentage.

In this study considered the application of Geogreen system in walls and roofs. Other studies, not included in this article, determine the number and type of support elements to be used in walls and roofs with the purpose of maximizing its efficiency and minimize the system cost. The results indicate that three support points are needed per module, which makes a total of 12 supports per m^2. The most effective elements for the vertical positioning of this system are stainless steel anchorage screws HILTY HUB-H8 with a 47 mm circular face stainless steel plate.

In this solution the wall irrigation is performed using polypropylene irrigation tubes inserted into opening along each modular element.

The substrate used is a common low weight substrate for green roofs. Plant selection can vary depending on the wall location and exposure to the surrounding environment. *Sedum* is commonly used in green roofs for its high resistance to different environments and low irrigation needs. Some *Sedum* varieties were also tested in a Geogreen wall and they also revealed better performance when compared to other local plant species.

The materials used in the production of the modular parts aim to minimize the environmental impact of this system. Each Geogreen modular element comprise 50% of industrial waste, namely mine waste mud from Panasqueira mines (43%) and milled waste glass (7%) (Fig. 2).

In addition, each module also includes 30% natural materials, such as expanded black cork board (27%) and expanded black cork granules (3%). These are classified as sustainable materials for its production process and materials used.

2. Methodology

This study uses a life cycle analysis (LCA) to identify the environmental impacts throughout the life cycle of the Geogreen system. It is carried out according to the LCA standard: ISO 14040:2006 and ISO 14044:2006.

2.1. Components

For this analysis the Geogreen system was subdivided into three main components:

1. Bare wall, where the system is fixed into;
2. Support, which includes the Geogreen modules and all supporting elements;

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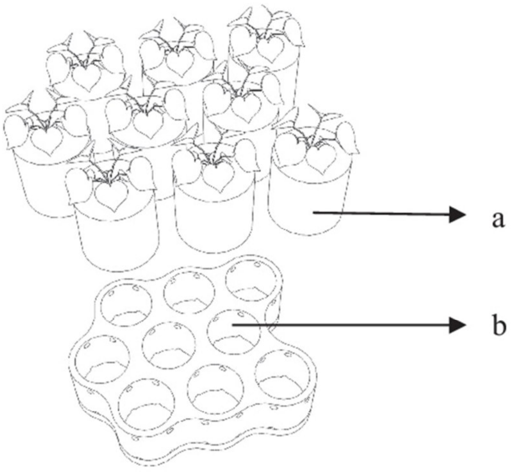

Fig. 4. Geogreen module with vegetation and substrate. a. Vegetation and substrate; b. Geogreen module.

3. Greening, which includes all elements related to the integration of vegetation.

The bare wall (1) is based on the characteristics presented by Ottelé et al. (2011). This element was quantified only with the purpose to allow a comparison of the Geogreen LCA with green wall systems studied by Ottelé et al. It comprises a conventional brick wall which includes: inner masonry wall with 10 cm of limestone, 10 cm of mineral wool insulation, 5 cm air gap, outer brick wall with 10 cm and finishing layer of mortar. This bare wall is used as a base to support and fasten the Geogreen system.

The support (2) includes all materials that make part of the Geogreen modules and allow it application in the walls and roofs. Each module comprises a base layer with an alkali activated precast slab and a top layer of expanded black cork board, bonded together by neoprene glue. Each module is fixed to the wall through three support points using stainless steel anchorage screws and circular stainless steel plates (Fig. 3).

The greening (3) includes the vegetation, substrate, irrigation and waterproofing (Fig. 4).

2.2. LCA study

According to life cycle assessment principles standards, an LCA study is structured in four main steps, namely: goal and scope definition (definition of the functional unit and system boundaries); life cycle inventory (inventory data of different production processes); life cycle impact assessment (inventory converted into environmental impact) and interpretation (results discussion).

2.2.1. Goal and scope of the study

The goal of the study is to build up the environmental profile of Geogreen system, in order to benchmark with other green wall's systems. The functional unit for analysis, in reference to the elementary school buildings, was defined as one square meter of Geogreen system

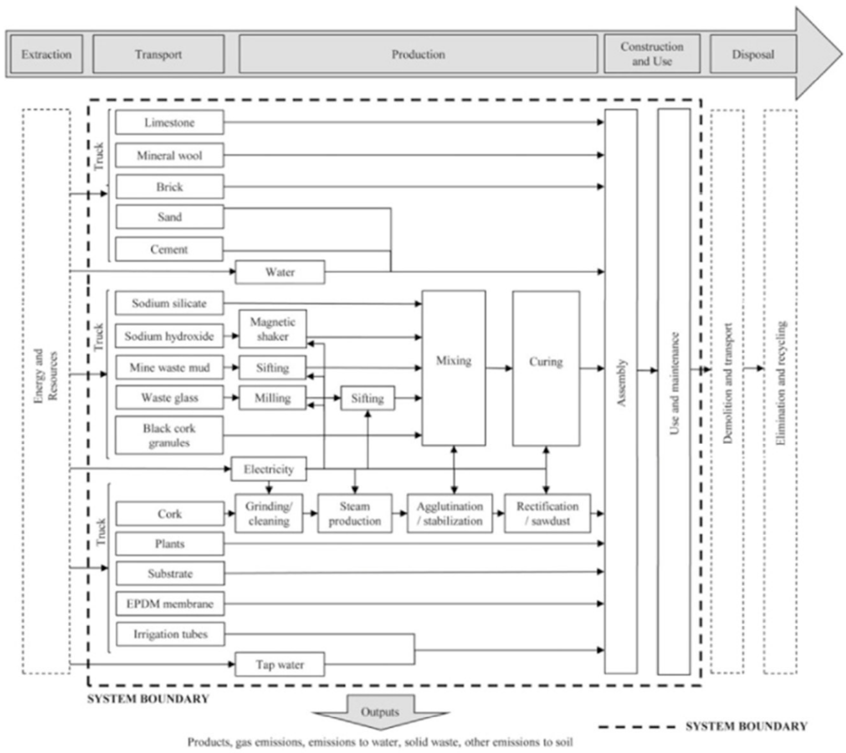

Fig. 5. Life cycle stages and product unit processes.

Table 1
Materials weight (kg) and service life (years) of Geogreen components.

	Components	Materials	Weight (kg/m²)	Service life (years)
Bare wall	Inner masonry	Limestone	147	50
	Insulation	Mineral wool	4,3	50
	Air cavity	Cavity	–	–
	Outer masonry	Brick (clay)	145	50
	Mortar	Sand + cement + water	84	50
Support	Alkaline activated board	Panasqueira mine waste mud	10,5	50
		Milled waste glass	1,7	
		Black cork granules	0,7	
		Sodium silicate	2,7	
		Sodium hydroxide	1,7	
	Expanded black cork board	Expanded cork board (80 mm 160Kg/m³)	6,5	50
	Fixing glue	Neoprene glue (Ceys Montack Express)	0,5	10
	Fastening	Stainless steel anchorage HILTY HUB-H8 + 47 mm circular face stainless steel plate	3,2	50
Greening	Substrate	Light weight substrate (Siroroof)	29,7	50
	Plants	*Sedum album*	5,9	10
	Waterproofing	EPDM membrane (2 layers)	0,1	10
	Irrigation system	Polyethylene tubes	0,8	10
	Water demand	Water use[1]	340,0	1

(1 m2) for a period of the life cycle. The lifetime of Geogreen system was defined as 50 years, which is the expected service life of a green wall.

We considered a “cradle-to-gate” life cycle analysis. The boundaries of the system include the Geogreen manufacture (Bate wall, support processes), construction (transport, assembly and construction-installation on-site processes) and use stage (Fig. 5). Geogreen environmental profile does not include raw materials extraction and disposal since there is no reliable data on both stages.

2.2.2. Life cycle inventory

The Geogreen manufactured (bare wall component) inventory data have been obtained from commercial data sheets and manufacturers.

The data for the materials used in the production of the alkali activated precast slab were obtained from the studies developed in the DECA-UBI laboratories of University of Beira Interior, Portugal. Table 1 shows which components and materials make part of the Geogreen wall system. This table also identifies each material weight per square m^2 and the service life of each element. The production of auxiliary materials, like screws, plates and adhesives and the energy production and distribution and roads, vehicles and infrastructures construction were excluded.

The transportation distances used, from where they were supplied, are all to and from Abrantes, Portugal. An average transport distance of 85 km was used. This location was used assuming that the Geogreen elements are produced in a location nearby to Sofalca plant. Sofalca is one of the main producers of expanded black cork. This location was assumed due to its proximity to the motorway and its central location in the Portuguese territory.

Although the period of analysis considered is 50 years the use stage considered for greening support (waterproofing, irrigation and plants) were 10 years maintenance. The water demand is based on one year of life service that is the necessary time for roots penetration and plants consolidation. So, for this study it is assumed that green wall is watered every day, during 6 months in the first year (spring and summer), using 8.7 l/m2, which is approximately 90 ml per plant.

This LCA study uses the GaBi 6 software and databases (Thinkstep, 2015[1]) for background data. The software used makes the study more efficient considering that GaBi 6 incorporated inventory databases and impact analysis methodologies. Nevertheless, it was necessary some inventory adaptation in planting process because there no specific database, therefore it was used soil as substrate. Once database don't allowing specific plant species, general vegetation was used. The Geogreen system proposes the use of planting adapted to local climatic conditions.

2.2.3. Assessing environmental impacts

The environmental profile of Geogreen system integrates three relevant and commonly impact categories used in similar studies (Ottelé et al., 2011): Global Warming Potential (GWP), Human Toxicity Potential (HTP) and Freshwater Aquatic Ecotoxicity Potential (FAEP). The Global Warming Potential (GWP) is related to the emission of greenhouse gas to the atmosphere. Human Toxicity Potential (HTP) concerns about the potential harm of toxic substances released into the human environment. Freshwater Aquatic Ecotoxicity Potential refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.

The environmental impacts were determined with GaBi 6 software and impacts were assessed by using CML 2001 impact assessment methodology[2] providing an Endpoint approach. The environmental profile doesn't take into account the environmental benefits of reusing waste materials, natural materials, and the capacity of plants to retain CO2 and other heavy metals. Besides, the LCA results were presented as kg equivalent, and no normalization or weighting were applied.

3. Results and analysis

3.1. Life cycle impact assessment

The environmental analysis of the three main components of Geogreen system (Bare wall, Support and Greening) demonstrates that the Support has the highest impact in all categories (Table 2). The detailed Environmental Profile (Table 3) reveals the alkali activated precast slab production process is the main environmental contributor. A detailed analysis identifies the curing process of the alkali activated precast slab as the highest contributor for all impact categories.

The alkali activated precast slab results demonstrate that the transport impact is residual in relation to the energy consumption, which represents around 97% of the total environmental burden (Table 4). Electricity production in Portugal is slowly reducing its dependency on fossil resources by increasing on renewable energy sources. However fossil resources still represents nowadays more than half of the energy source used in thermoelectric and hydroelectric power stations (REN, n.d.).

The alkali activated precast slab high environmental impact results from a long curing process, which has a high energy demand and is entirely based on the consumption of electricity. The curing process of alkali activated precast slab is done in the laboratory in a ventilated oven for 7 days at 60 °C (Option 1). In an industrial production process of the Geogreen system, alternatives could be identified, like using a more energy efficient curing process, or other ways of accelerating the activation process. Further laboratory studies demonstrate that the curing process can be accelerated in a ventilated oven for only 24 h and then allowing the curing process to continue at room temperature until reaching

[1] References:
ThinkstepGaBi Software, Version 6.2; ThinkStep. Leinfelden-Echterdingen, Germany (2017).
[2] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, J.A. de Bruijn, R. van Duin, M.A.J. Huijbregts (Eds.), Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in Industry and Science, 1-4020-0228-9, Kluwer Academic Publishers, Dordrecht(2002) (Hardbound; Paperback, ISBN 1-4020-0557-1).

Table 2
Geogreen system environmental profile.

	Components/processes		GWP 100 years [kg CO2-equiv.]	HTP inf. [kg DCB-equiv.]	FAETP inf. [[kg DCB-equiv.]
Bare wall	Inner masonry		1,41	3,60E-02	7,20E-03
	Insulation		1,27E-01	3,26E-03	6,46E-04
	Outer masonry		1,81	4,60E-02	9,18E-03
	Mortar		1,95E-01	5,00E-03	9,97E-04
Support	Alkali activated precast slab	Mine waste mud	3,03E-01	6,70E-02	1,20E-03
		Milled waste glass	4,80E + 00	2,49E-01	7,41E-03
		Black cork granules	2,50	1,02E-01	3,06E-03
		Sodium silicate	8,10E-02	2,20E-03	4,36E-04
		Sodium hydroxide	1,10	3,74E-02	1,41E-03
		Mixing	1,86E-01	9,63E-03	2,88E-04
		Curing	1,19E + 02	4,88	1,46E-01
	Expanded black cork board		3,61	1,46E-01	4,81E-03
Greening	Substrate		8,10E-01	2,10E-02	4,30E-03
	Plants		8,03E-01	7,50E-03	6,00E-03
	Irrigation		3,68E-01	2,20E-02	2,96E-03

28 days (Kastiukas et al., 2017). This change on the curing process is expressed on Option 2 (Fig.6).

On Option 2 the curing process represents 62% of the total GWP of the alkali activated precast slab. This is followed by glass milling and sieving (18%) which is also energy demanding and time consuming, and results from a non-industrialized process.

Globally the introduction of this improvement in the curing process has a higher impact on the GWP. It represents a total reduction of 74% in the GWP, from 138 kg CO_2 equiv. to 36 kg CO_2 equiv.

3.2. Comparison with other LCA studies

Ottelé et al. presents a comparative LCA of green facades and living wall systems. Results demonstrate that environmental impact differences are mainly caused by the supporting material and the replacement both for plants and material. Direct greening systems have very small environmental burden due to the fact that there is no additional material involved. Indirect greening systems have a higher impact profile due to the use of stainless steel which has no potential to be recycled. In fact green facades show the lowest results, however full façade coverage can take up to 20 years to be achieved. Living wall systems reveal higher environmental burden. However they allow a rapid coverage of the entire surface and a higher variety of vegetation. The highest environmental burden was obtained by the living wall system based on felt layers, due to its difficulty to recycle this panel. This study also demonstrates that the benefits for heating for the living wall systems are more than three times the direct and indirect greening systems. This is mainly caused by the contribution for the insulation properties of the materials involved (Ottelé et al., 2011). The Geogreen system is also modular living wall system. When compared to the living wall systems evaluated by Ottelé et al. it can be noticed that the Geogreen system has the lowest impacts of all living wall systems on all three categories, GWP, HTP and FAETP. Also it is important to mention that the Geogreen system was tested on a wall in a location with Mediterranean climate conditions. The obtained results demonstrated that this system can reduce thermal gains by conduction in 75% in warmer days and thermal losses in 60%, during heating season (Manso and Castro-Gomes, 2016).

The Geogreen system was developed either for green roofs or green walls. LCA results can be compared with other green roof systems if only the support and vegetation are considered. Vacek et al. developed an LCA study of four semi-intensive green roof assemblies (Assembly 1, Assembly 2, Assembly 3 and Assembly 4) (Vacek et al., 2017). A comparison with these results demonstrates that a Geogreen roof system (with Option 2) would have almost half the impact on GWP than all Vacek et al. solutions.

Han et al. presents also a LCA of a cladding system using ceramic façade panels (CFP) (Han et al., 2015). The results on a "cradle to gate" approach are 14% lower on Global Warming Potential but 7 times bigger on Human Toxicity Potential.

La Rosa et al. presents four systems as alternatives of external walls for buildings (Systems A, B, C, D) (La Rosa et al., 2014). Geogreen system presents a lower impact on all the selected categories when compared to these four systems (Fig. 7).

4. Conclusions

In conclusion life cycle analysis (LCA) can be an important tool of decision making, allowing to identify which materials and processes have the greatest impact in the overall environmental burden.

Considering the number of processes involved, this study subdivides the Geogreen system into three main components, the bare wall, support and greening. From the environmental analysis of these results it can be noticed that the support has a major impact on all the selected categories. This becomes more evident in GWP, representing 96% of the total environmental burden of this category.

Table 3
Detailed environmental impacts of Geogreen system.

Impact categories	Unit	Bare wall	Support	Greening	Total
GWP 100 years	[Kg CO_2-equiv.]	3,59	133,14	1,98	138,71
HTP inf.	[Kg DCB-equiv.]	0,09	5,43	0,05	5,57
FAETP inf.	[Kg DCB-equiv.]	0,02	0,16	0,01	0,20

Table 4
Environmental contribution of transport and electricity in alkali activated precast slab.

Impact categories	Transport	Electricity	Others
GWP 100 years	0,28%	97,00%	2,72%
HTP inf.	0,15%	97,50%	2,35%
FAETP inf.	0,97%	96,47%	2,57%

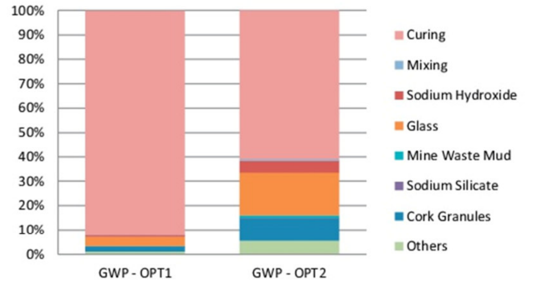

Fig. 6. GWP comparative analysis of production processes of alkali activated precast slab.

The LCA study was important to detect what's the source of most carbon emissions. This study allowed identifying that the Geogreen system has a curing process with a major impact on GWP. By changing the curing process it became possible to reduce 74% the overall GWP of the Geogreen system.

The GWP is directly related to the dependency on fossil resources for energy production and transportation to a certain location. In this study a note was also added to the fact that the dependency of fossil resources for the production of electricity in Portugal is decreasing from year to year. This means that the GWP of this product has a tendency to also decrease.

Also LCA helps to establish a comparison between systems and understand their differences with regard to their impact on the environment. When comparing the obtained results with other LCA studies for green walls, green roofs, cladding systems or external wall systems it can be noticed that Geogreen system is one with the lowest environmental burden on Global Warming, Human Toxicity and Freshwater Aquatic Ecotoxicity. This study demonstrates that greening systems can still be innovative and incorporate strategies like the use of recycled materials or industrial waste to contribute to a lower environmental impact and therefore make green roofs and green walls more competitive cladding solutions.

To fully validate this proposal, this study must be extended to a "cradle to grave" approach. Finally, overall consideration regarding transport distance, environmental, social and economic interests can be discussed in future studies.

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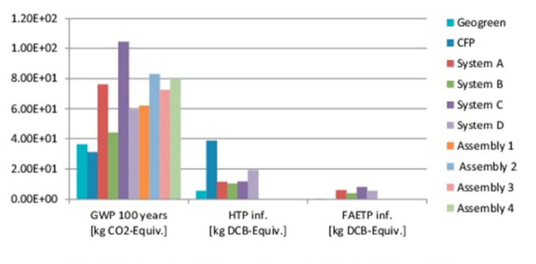

Fig. 7. Comparison of Geogreen system with other LCA studies.

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Chapter 9

Conclusions and recommendation for future work

This chapter describes the main conclusions that result from the research work presented in this thesis. It also discusses a few research topics related with the work developed in the doctoral programme that may be addressed in the future.

1. Conclusions

Due to an unsustainable growth of urban areas it is becoming increasingly important to find new strategies to improve their environmental conditions. The integration of vegetation in the urban context can be an important tool to minimize some environmental problems like the "greenhouse effect", surface runoff and air quality deterioration, benefiting both the urban context and buildings environment. The use of vegetation in the built environment has been proven to have several environmental, social and economic benefits leading to a growing research on this subject.

Also, mine waste deposition is a global environmental problem which must be addressed, representing 28% of the total waste produced in European Union [1]. Therefore it is becoming mandatory to find new construction solutions with added value that contribute to the reuse of mine waste and other recycled materials, in order to minimize their environmental impact.

This thesis is focused on the concept design of a new modular system for vegetated surfaces, like green walls and green roofs, integrating alkali activated mine waste materials and other recycled materials. Also this research work is focused on testing the characteristics of this new modular system in order to identify how it can contribute to improve buildings comfort (thermally and acoustically), and also act as a sustainable strategy for buildings.

The research work was divided into several steps. First was developed a systematization of current and innovative solutions of green roofs (Chapter 2) and green walls (Chapter 3). This was followed by the analysis of how these systems can contribute to urban design (Chapter 4). After, based on lessons learn from the existing solutions, a new modular design solution for vegetated surfaces was developed using innovative materials like alkali activated mine waste mud and other recycled materials (Chapter 5). In this context, alkali-activated materials properties were tested to improve its suitability to the proposed modular system (Chapter 6). Also, thermal and acoustic characteristics of this system were determined (Chapters 7 and 8, respectively). Finally, was developed a study on the life cycle analysis of the new modular greening system, regarding to the choice of materials and production processes (Chapter 9).

Each of these research steps resulted in contributions of this thesis to the accomplishment of the main goal of designing an innovative modular system for vegetated surfaces using alkali activated materials.

State-of-art of green roofs and green walls

This work complements the knowledge in the field of vegetated surfaces, namely green roofs and green walls. It presents a systematization of existing green roof and green wall systems and analyses their general requirements. Also, in this study is included a bibliographical review of the benefits associated with these cladding systems, both for the urban context and for the built environment.

From the analysis of different types of green roofs and green wall systems, it can be understood that there is a significant evolution in this field. Modular systems are relatively new solutions in the field of green roofs and green walls. They have advantages as they enable the installation and removal of each module individually, simplifying the installation and maintenance processes. Most recent continuous solutions focus in the use of lightweight materials with reduced thickness, covering the entire surface with greenery as quickly as possible. This can be particularly useful when applied in buildings rehabilitation.

In fact, most recent applications of new living wall systems in new and refurbished buildings is often seen as a landmark in urban fabric. This demonstrates that the use of vegetated surfaces can play a decisive role in the requalification of urban image.

Generally, the innovation of all these systems is mostly centered in the improvement of design to achieve a better performance mainly through the integration of water retention materials and drainage means.

Also, systems adaptability is still a field of development. Most solutions are designed to be applied in only one type of surface. New solutions must evolve and adapt to different surfaces and inclinations with the convenient adaptations.

Systems for vegetated surfaces must also evolve to become more sustainable solutions [2] through the use of materials with less incorporated energy and CO_2 emissions and through the application of climate adapted plant species with less irrigation needs.

Design of a modular system for vegetated surfaces

This work presents the design of modular system to create vegetated surfaces in new and existing buildings. It aims to be of simple assembly and disassembly, allowing to create vegetated surfaces quickly and effectively. It can be adaptable to different surfaces and inclinations, allowing its application in the construction or rehabilitation of roofs, facades and other built elements.

This work explores new possibilities of designing modular elements for green roofs and green walls using new shapes and geometries through moulding, CNC cutting and milling. The modular elements can acquire different configurations and inclinations according to the needs of application and architectural context.

In this work were studied the constructive characteristics of a new modular system for green roofs and green walls. In the scope of this study are also included the materials selection and fastening method. Each module of this system consists of a base made of a porous and resistant alkaline activation material, a light upper element in insulation cork board and endemic plant species. The fastening system of these modular elements is calculated with the aim of providing their application both in roofs and walls, and also to minimize the number of support elements per piece.

The sustainability of vegetated surfaces is a subject that still needs to be evaluated. This work also focuses on the integration of sustainability strategies in the development of this modular system. The application of alkaline activation materials results from the aim of promoting waste recycling and reuse, contributing to the minimization of the consumption of natural resources. The integration of these materials functions as a strategy to absorb water and transmit it slowly to the plants. The use of vegetation adapted to the local climate simultaneously aims to minimize the need for irrigation, while contributing to the retention of carbon dioxide.

The application of insulation cork board (ICB) in the modular system results from the intention of using sustainable materials with a low environmental impact. In addition, this material has thermal and acoustic properties that can contribute to the environmental comfort of built spaces.

The proposed modular system for vegetated surfaces differentiates itself from other existing green roofs and green walls by its constructive characteristics, incorporation of industrial waste materials and integration of sustainability principles.

Application of alkaline activation materials in vegetated surfaces

The presented studies demonstrate an evolution in the knowledge of alkaline activation materials using industrial waste in their composition and their integration in new architectural applications, namely in a modular system for green roofs and green walls.

The tests for new compositions of alkaline activating materials (geopolymers) are based on mixtures that reuse industrial waste (Panasqueira mines and recycled glass) and the addition of several aggregates (sand, expanded cork granules and expanded clay). This study is based on the equipment and knowledge available in the C-MADE Research and Development unit, about alkaline activation mixtures using mine waste and other materials. Recent studies have shown that mud waste from Panasqueira mines has a high alumino-silicate composition and is considered a very promising material for the production of alkaline activation materials, both from an environmental and economic point of view. Alkaline activation materials (also known as geopolymer binders) obtained to date has high compressive strength, good abrasion resistance and acid resistance. It was also verified that the leaching of heavy metals from alkaline activation materials obtained from Panasqueira mines mud waste is very small, demonstrating that alkaline activation as a very safe process of encapsulating these metals [3] [4].

The alkaline activation mixture to be used as reference was subjected to several combinations in order to obtain a blend with the best compressive strength results. In this context, several percentages of each precursor (mud and glass), different curing temperatures and molar concentration of sodium hydroxide were tested.

After defining the reference mixture several types of aggregates were added with the intention of maximizing its water absorption capacity and minimizing the mixture density. Tests indicate that all mixtures with sand have a higher bulk density than reference mixture and expanded clay mixtures have the lowest water absorption coefficients.

Results demonstrate that expanded cork granules are considered the most suitable aggregate to be added to the alkali activated mixtures. Adding 25% of expanded cork granules into the reference mixture can reach to a maximum compressive strength of 17 MPa, while reaching to one of the highest water absorption coefficients with 4,77 $kg/m^2.h^{0,5}$ and one of the lowest densities with 1,85 g/cm^3.

Improvement of buildings thermal conditions

Real climate tests were performed in Covilhã, Portugal, to determine the thermal performance of the proposed modular system for vegetated surfaces.

Several prototypes were installed along one wall of an outdoor test cell built for this purpose in the University of Beira Interior facilities. Real climate tests were performed comparing a bare wall (Reference wall) with a similar one covered with the proposed modular system (Geogreen wall) under the same environmental conditions. The research focused on the comparison of interior surfaces temperatures and heat flux between Reference wall and Geogreen wall in three different periods.

Thermal analysis of this new modular system in real climate conditions demonstrates that it:

- Offers an additional thermal protection to temperature variations even without vegetation and substrate in its openings;
- Improves thermal comfort of indoor spaces by reducing the interior thermal amplitude of walls, decreasing and delaying walls heat flow between the interior and exterior;
- Introduces an increased attenuation of interior surface temperatures when applied with plants and substrate. Reducing maximum interior surface temperatures and increasing minimum interior surface temperatures up to 7ºC, during heating season;
- Has impact on the thermal wave damping. It contributes to decrease the average daily interior thermal amplitude (Average ΔT_{ref} - Average ΔT_G) in 11.3ºC, during heating season;
- Helps to mitigate heat transfer by increasing the thermal delay between the exterior and the interior;
- Reduces thermal gains by conduction in 75% in warmer days and thermal losses in 60%, during heating season;
- And contributes to reduce the exterior surface temperature up to 15ºC.

In summary, this solution can contribute to the improvement of buildings thermal performance providing more thermal comfort for buildings occupants.

Improvement of acoustic conditions

The sound absorption of a modular system for green surfaces was tested in simulated conditions. This study aimed to identify how factors such as substrate and plants, variety and height of plants, affect the sound absorption of this modular system.

For this purpose, four different setups were prepared. The first consisted on testing the modular elements without substrate and plants (S1). The second one included the same modular elements containing substrate (S2). A third test was performed using the modular elements with substrate and plants with an average height of 7-8 cm (S3). The latest had the same elements as setup S3, however 10% of the plants with 7-8 cm high were replaced by plants with an average height of 25-30 cm (S4). Additionally, the research aimed to establish a sound absorption comparison between the modular system and a mineral wool sample, set as a reference material (REF).

First results demonstrate that the proposed modular system has good sound insulation characteristics, obtaining a classification as absorbent material in all setups.

The lowest sound absorption coefficient (0.4) was obtained in the first setup (S1) where modules where placed in the reverberation chamber on their own. Results were quite promising when compared to other cladding materials like brick, plaster or tiles. This may result from the fact that the GEOGREEN system has a non-uniform top layer of expanded cork board, a highly porous material, which allows acoustic waves to be absorbed.

The introduction of low weight substrate into the modules (S2) enabled to improve the weighted sound absorption coefficient in 15%.

The presence of vegetation (S3) improved the weighted sound absorption coefficient 20% more. However, replacing 10% of plants with 7-8cm high by plants with 25-30cm high (S4) resulted in an improvement of 5% of its weighted sound absorption coefficient (αw), which increased from 0.75 to 0.80. On the other side the variety of plants showed influence also in the absorption class, which reached a class B.

A comparison with other tested systems revealed that setup S4 has a more effective sound absorption than systems tested by other authors, especially on higher frequencies, reaching to a sound absorption coefficient of 0.8 at 500Hz.

Life cycle analysis

A comparative life cycle analysis (LCA) was also carried out in order to evaluate the environmental impact of this modular system. The aim was to evaluate the environmental impact of a new modular system for green roofs and green walls which uses waste and sustainable materials in its composition. LCA was developed to evaluate the long term environmental benefits of this system considering a "cradle to gate" approach.

The Life Cycle Analysis (LCA) of Geogreen wall system allowed identifying a curing process with a major impact on Global Warming Potential (GWP). Changing the curing conditions allowed reducing 74% the overall GWP of the Geogreen wall system.

This LCA study also included a comparison with other systems to better evaluate its impact on different categories. In comparison with other LCA studies for green walls, green roofs, cladding systems and external wall systems it can be noticed that Geogreen wall system is one with the lowest environmental impacts on Global Warming, Human Toxicity and Freshwater Aquatic Ecotoxicity.

In summary, the Geogreen system aims to contribute as a passive design solution for buildings, associating the benefits of vegetation in buildings with the thermal, acoustic and environmental characteristics of the associated materials.

2. Recommendation for future work

This study consists in promoting materials reuse through the development of a high value product from waste materials. The aim is to provide unique properties to the system and create a more sustainable solution than the conventional extensive green roofs and modular living wall systems. The intention is to develop a product with added value, which can make environmentally and economically viable transforming industrial waste materials [5, 3]. Based on the reuse of industrial waste, alkali-activated materials are integrated into this modular system with the purpose of absorbing water and slowly release it to the plants, minimizing its irrigation needs.

This study isn´t enclosed on itself. Designing a new solution for vegetated surfaces is an iterative process that is in constant evolution.

Other configurations, dimensions or compositions are also possible, provided that continuity of the system is ensured and that each element is not excessively heavy. Some configuration alternatives were presented in the Patent (PT106022) of this system. These configurations show how the form of this system isn´t enclosed to a single proposal, allowing it to take other shapes and sizes. However is important to keep the goals of manually install the system, dismantlement for maintenance purposes and use in buildings rehabilitation.

There is also the opportunity to redesign this system using other materials. As example, the use of alkali activated materials is a very recent field of study which is still subject of discussion and analysis. Recent studies demonstrate that the density of these materials can be reduced with the addition of aluminium powder and hydrogen peroxide to produce foamed lightweight materials [6]. Also their water absorption capacity is significantly changed which can be an important strategy of water retention for the modular system.

The results demonstrate that this solution can contribute to improve buildings thermal performance in order to provide a better thermal comfort for buildings occupants. Further studies may comprise the thermal behavior analysis of this modular system during a cooling season, namely to determine its potential as passive cooling system. Also it is important to understand how this system can contribute to reduce and time shift cooling load peaks, avoiding oversized air conditioning systems, with higher energy consumption.

The implementation of real case examples with these modular elements in the external envelope of buildings, either in roofs or walls, would also be important to evaluate its performance in real conditions, considering the growth of different types of vegetation along the years.

The present study shows that the proposed modular system has good sound absorption properties. However its contribution can still be improved based on the design and plants used, which can bring to new ways of further development and research directions. Other studies have also demonstrated the noise reduction potential of green walls and green roofs. Therefore, further research can be performed to identify the actual contribution of this system to noise reduction in adjacent rooms. Also, to fully validate the Life Cycle Analysis of this modular system, this study can also be extended to a “cradle to grave” approach. Also, overall consideration regarding transport distance, environmental, social and economic interests can be discussed in future studies.

It is important to notice also that the cost of Geogreen prototypes was estimated considering all its prototype components. There isn´t still an industrial production process behind this solution which makes it more difficult to compare it with other systems existing on the market. From the obtained results is becomes notorious that the cost of natural plants (34%) have a major impact on the global cost of the Geogreen system. In fact if adapted plants are produced locally this may influence the cost of each plant and consequently the cost per m^2 of the system. An alternative would be also to redesign the system to reduce the amount of plants per m^2 allowing them to grow more. This may affect the period needed to obtain a full coverage of the wall, and also result on a reduction of vegetation maintenance. Acquiring further information regarding the production process of this solution would also be important to perform a life cycle cost analysis of this system. This study could be very helpful for the decision making and competitiveness of this system in the market.

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