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Used engine oil as alternate binder for buildings – a comparative study

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At present, global warming and climate change are the major challenges of foremost significance that substantially influence the earth's environment. The construction sector, especially buildings, is one of the largest sources of greenhouse gas emissions. Conventional building materials such as clay bricks and cement are considered as environmentally unfriendly due to enormous emissions during their production. This paper investigates the utilisation of used engine oil (UEO) as an alternative to the usual cementitious binders. Prototypes were produced from UEO to optimise the compositions and conditions of the process and tested for compressive and flexural strength, permeability and water absorption, respectively, following the ASTM standards. Furthermore, environmental and weathering aspects were also demonstrated to ensure the feasibility of the product. Samples constituting 5% by weight UEO have shown significant results for flexural stress, compressive strength and water absorption and also passed the permeability test. Moreover, 5% of UEO samples have negligible effect in strength for accelerated weathering conditions as demonstrated by the ultraviolet test. Conclusively, UEO can be used as a replacement to conventional binding materials such as a clay bricks and cement. Sustainable development and waste management are the hallmarks of this research.

Notation

A	cross-sectional area of the resisting load
C	distance from the neutral axis
f_c	compressive strength
I	moment of inertia
M	unit load
P	load
W_A	mass in air
$W_W T_0$	mass in water at zero time
$W_W T_{24}$	mass in water after 24 h
σ	flexural stress

1. Introduction

Greenhouse gases (GHGs) are considered the prime cause of global warming that influences the climate of the earth due to rise in temperature and occurrences of disasters. Use of fossil fuels and industrial activities are considered as some of the main sources of GHG emission. Carbon dioxide (CO_2) is the leading contributor in global warming compared with other GHGs emitted. Notably, cement, a concrete binding material, is solely responsible for ~5% of all carbon dioxide emitted globally, as highlighted by International Energy Agency (Tanaka, 2009). Moreover, production of clay bricks requires around 2–3 d and a temperature >1000°C (Forth and Shaw, 2013). The process to produce a ton of bricks needs energy of ~1·84–2·8 kJ/kg during which 184–244 kg of carbon dioxide is emitted. Thus, conservation of energy and natural resources has become significant to foreshorten global pollution and wastage. These serious concerns have led the construction sector to replace the masonry units, in particular, cementitious and clay-bound materials with recycled and waste materials.

Several million tons of the used engine oil (UEO) is produced every year as a waste product from the automotive industry (Bloch, 2012). According to Energy Information Administration (EIA, 2006), around 1·35 billion gallons of all oil types were disposed of illegally. Moreover, UEO is found to be one of the most commonly disposed of waste petroleum products that severely affect the water sources and consequently human health (Alongi, 2012). It has been found that around one million gallons of water is polluted by approximately one gallon of UEO discharged of through drainage (Kamal *et al.*, 2014; Swain, 2003). In order to preserve nature it is suggested that it is better to recycle waste products rather than releasing them into the environment. It is found that UEO can act as concrete plasticiser and could improve the fluidity or workability of freshly mixed concrete (EPA, 2014). UEO can be recycled and reused; however, once it gets contaminated with water or other solvents it can no longer be recycled. Utilisation of such waste oil for alternate purposes rather than disposing of it could be beneficial for improving the quality of environment.

Fly ash, especially when produced in an incinerator for the generation of electricity is considered a hazardous waste and most of this waste is being dumped into landfills (Adams, 2015). It is found that pulverised fly ash (PFA) could be used for the fabrication of ceramic tiles (Haiying *et al.*, 2007). Using PFA as filler significantly provides a lot of advantages. According to the American Coal Ash Association, using PFA can increase the durability of the binding material, reduce energy consumption and conserve other natural and raw materials (Adams, 2015). However, researchers also reveal that PFA content >50% in aggregates could not only foreshorten the workability but also increase the difficulty in compaction of the mixture (Garbacz and Sokołowska, 2013).

Substituting the waste aggregates has been the main priority of researchers in the past rather to replace the masonry units that are believed to be responsible for GHG emissions in the building industry. It is revealed that the production of cement that is used in concrete tiles and the kiln firing process that is used in the production of clay tiles are the chief contributors to high embodied energy and embodied carbon (Jones and Hammond, 2008). Contrary to masonry units, aggregates have a negligible impact on the environment since they have lower embodied energy and embodied carbon. Thus, replacing the masonry units with waste materials could reduce the GHG emissions by a significant margin. Researchers have already proven that vegetable oil mixed with aggregates followed by compaction and curing can produce building units (Forth and Zoorob, 2012; Nadeem *et al.*, 2017). The intent of the current investigation is to replace the traditional environmentally unfriendly binders such as clay and cement with UEO. Tile samples were examined for compressive and flexural strength, water absorption and permeability according to ASTM standards. In addition, energy and weathering aspects of these novel tiles were also evaluated.

2. Materials and methods

2.1 Materials

2.1.1 UEO

UEO was collected from different automobile shops in Kampar, Malaysia. The viscosity and specific gravity calculated were 170·5 centipoises (cP) and 0·92, respectively.

2.1.2 Natural aggregates

Sieving analysis of sand was carried out in accordance with ASTM standards (ASTM C 136 (ASTM, 2014)). However, PFA was collected from the nearby Tenaga Nasional Berhad power plant station in Manjung Setiawan, Perak. PFA of size <75 μm was used as filler in the production of samples.

2.1.3 Control samples

Control samples having a thickness of 25 and 100 mm and containing 25% filler, 15% cement and 60% sand were collected for comparison from the local manufacturer in Kampar, Malaysia, and designated as C_{15}.

2.2 Methodology

Mixing proportions and the mixing ratio are considered as important criteria for achieving the best binding effect. The UEO content varied between 3·5 and 6·5% based on the observation that it does not cause stickiness and gulping with the aggregates. Moreover, a filler content of 25%, a temperature of 190°C and a curing time of 5 d (Habib *et al.*, 2015) were considered as suitable for the production of UEO tile samples. Samples that contained 3·5, 4, 5, 6 and 6·5% (by weight) UEO were designated as $T_{3\cdot5}$, T_4, T_5, T_6 and $T_{6\cdot5}$, respectively. Initially, prototypes with 100 mm diameter and 25 mm thickness were produced by varying the UEO content mixed with 25% PFA and different proportions of sand to find the optimum binder for the production. After attaining the optimum compositions for UEO tiles, prototypes of thicknesses of 25 and 100 mm were manufactured. UEO prototypes and control samples with 25 mm thickness were then tested for flexural strength, water absorption, permeability and ability to withstand ultraviolet (UV) light while samples having 100 mm thickness were examined for compressive strength. Finally, UEO tiles having standard dimensions (390 × 240 × 30 mm) were produced and tested for water absorption, flexural stress, compressive strength and permeability, respectively, following the ASTM standards. Moreover, tests for environmental aspects for UEO tile samples were also carried out by calculating the embodied energy and embodied carbon, respectively. Embodied energy and embodied carbon for UEO was assumed to be 8 MJ/kg and 1 kg carbon dioxide equivalent based on transportation and processing charges. Embodied carbon was calculated from the carbon calculator based on the assumption that ∼1 t of UEO was collected from a distance of 400 km. Embodied energy and embodied carbon of other constituents used in the production of UEO tile samples were also determined and summed up to attain the total embodied energy and embodied carbon per UEO tile. Finally, economic considerations for cemented and UEO tiles were evaluated based on raw materials used and utility charges, while labour and other miscellaneous charges were excluded.

2.3 Testing procedure

The testing procedure is listed in the following section.

2.3.1 Water absorption

Percentage of water absorption for the samples can be calculated by the following equation in accordance with ASTM standards (ASTM C 67-13 (ASTM, 2013); ASTM C 1492-03 (ASTM, 2009))

$$1. \quad \text{Absorption\%} = \frac{W_{\mathrm{w}}T_{24} - W_{\mathrm{w}}T_0}{W_{\mathrm{A}} - W_{\mathrm{w}}T_0} \times 100$$

where W_{A} is the mass in air, $W_{\mathrm{W}}T_0$ is the mass in water at zero time, $W_{\mathrm{W}}T_{24}$ is the mass in water after 24 h.

2.3.2 Compressive strength

Compressive strength reported in MPa or psi can be calculated from the ratio of failure load to the cross-sectional area that resists the load. It was determined by using ASTM standards (ASTM C 67-13 (ASTM, 2013))

$$2. \quad f_{\mathrm{c}} = \frac{P}{A}$$

where f_{c} is the compressive strength, P is the load, A is the cross-sectional area of the resisting load.

2.3.3 Permeability

ASTM standards (ASTM C 1167-03 (ASTM, 2012); ASTM C 1492-03 (ASTM, 2009); Johansson, 1995) were used to determine the permeability of both prototypes and standard tiles. A permeability test was conducted by placing the samples horizontally and sealing the sides properly with a sealant to prevent leakage. UEO tile samples were then placed on a stand in such a way that its undersides remained visible and water of up to ~10 mm in height covered the samples for 24 h. The water drops were inspected after 24 h and the presence of two or more water drops on the underside of the samples was an indication that the samples were significantly permeable.

2.3.4 Flexural stress

Flexural strength calculated in psi or MPa can be demonstrated by ASTM standards (ASTM C 67-13 (ASTM, 2013); ASTM C 1492-03 (ASTM, 2009))

$$3. \quad \sigma = \frac{MC}{I}$$

where σ is the flexural stress, M is the unit load, C is the distance from the neutral axis, I is the moment of inertia.

3. Results and discussion

3.1 Fourier transform infrared spectroscopy (FTIR) analysis

FTIR analysis is considered an important tool to identify the by-products, contaminants and additives within UEO. FTIR analysis of UEO and virgin engine oil was conducted and the results are displayed in Figure 1.

It is revealed from Figure 1 that a strong functional group of alkyl C–H stretch and alkane C–H were observed in both the virgin and used oil samples. This is because engine oil is actually a long-chain polymer of an aromatic hydrocarbon. The oil is typically composed of 73–80% weight/weight aliphatic hydrocarbons 11–15% mono-aromatic hydrocarbons; 2–5% di-aromatic hydrocarbons; and 4–8% poly-aromatic hydrocarbon (Vazquez-Duhalt, 1989). There exists an impurity group in most polymer parts in the UEO sample, including carbonyl (C=O) and carboxyl (COOH) groups. This is a sign of oxidation in the oil due to the formation of C=O and COOH groups. This indicates that the engine oil used in vehicles gets oxidised partially during the combustion.

3.2 Size gradation of sand

Size gradation was carried out for sand following the ASTM C 136 (ASTM, 2014). Sieve analysis of sand is presented in Table 1. It shows that more than 99% of the sand passes through a 3·35 mm sieve.

3.3 Optimisation of parameters

Prototypes were produced with different percentages of oil mixed with sand and filler and the results based on physical observation are shown in Table 2. From the preliminary results shown in Table 2, it can be concluded that T_4, T_5 and T_6 samples could be further investigated since they showed appreciable results. However, samples with 3·5 and 6·5% of UEO were found to be brittle and can no longer be suitable for further testing. So, prototypes produced from 4, 5 and 6% of UEO were evaluated as the initially optimised binders for the production of UEO tiles.

3.4 Water absorption

Water absorption test is tremendously important because the failure of most building structures is due to the additional penetration of water and aggressive agents such as chlorides and sulfates. The rate of water absorbed by a material gives useful information about the pore structure, permeation characteristics and durability of the concrete (Parrott, 1992). Percentages of water absorption were calculated for optimised UEO prototypes and control samples having 25 mm thickness and are displayed in Figure 2.

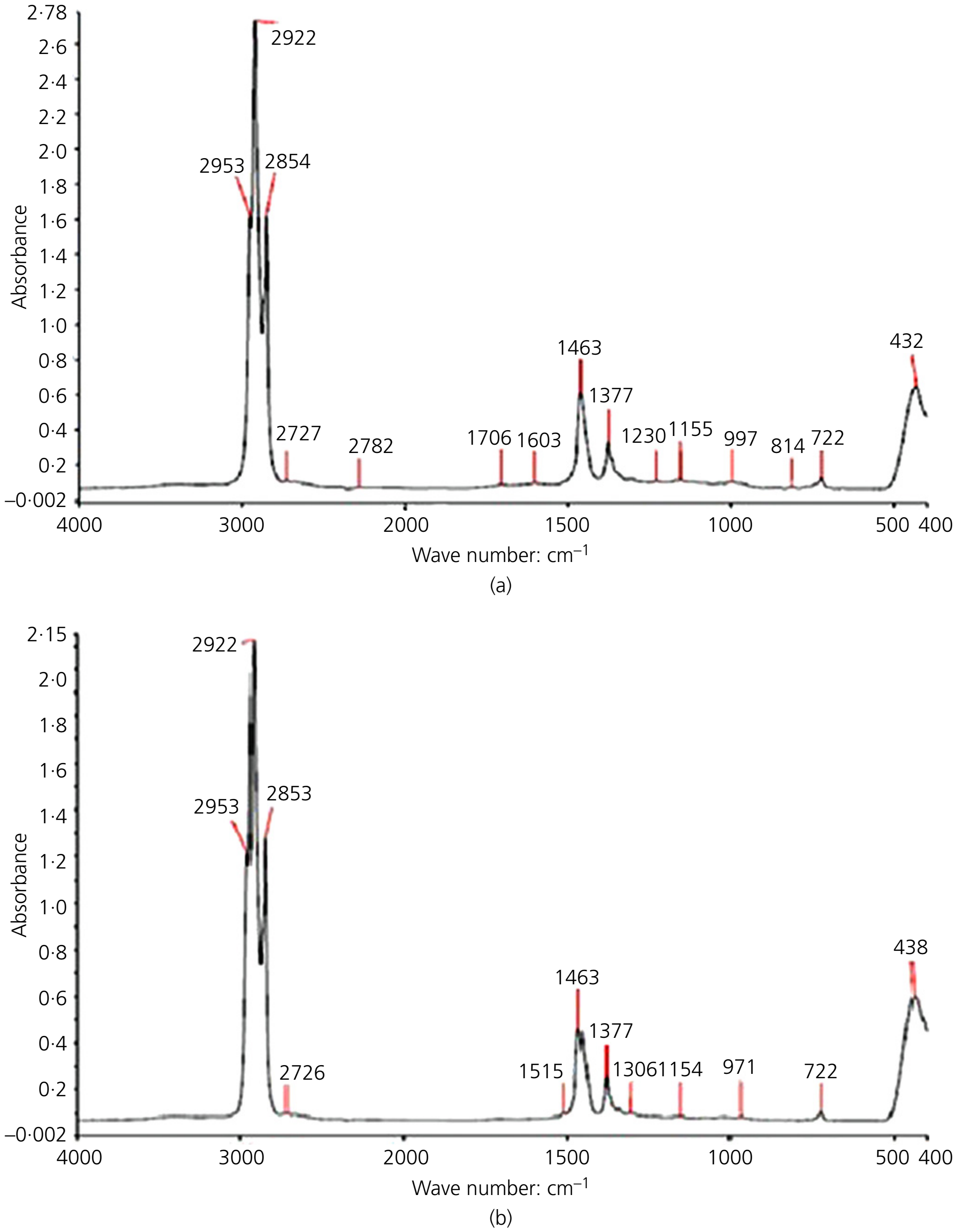

Figure 1. FTIR analysis of (a) used and (b) virgin engine oil

Table 1. Sieve analysis of sand

British standard sieve size: mm	Weight retained: g	% Weight retained	Cumulative % retained	Total passing: %
3·35	9	0·9	0·9	99·1
2·36	21	2·1	3·0	97·0
1·18	317	31·7	34·7	65·3
0·425	370	37·0	71·4	28·6
0·212	210·4	21·4	92·8	7·2
0·15	18	1·8	94·6	5·4

Table 2. Description of prototypes samples produced from different compositions of UEO

Specimen number	Compositions	Observations	Conclusion
$T_{3\cdot5}$	3·5% oil 25·0% fly ash 71·5% sand	■ Sample can support self-weight but rupture when injected ■ Can be broken by hand	No further testing
T_4	4·0% oil 25·0% fly ash 71·0% sand	■ Sample can support self-weight	Testing to proceed
T_5	5·0% oil 25·0% fly ash 70·0% sand	■ Sample can be considered one of the most stable ratios	Testing to proceed
T_6	6·0% oil 25·0% fly ash 69·0% sand	■ Sample seems a little too wet but is able to support self-weight	Testing to proceed
$T_{6\cdot5}$	6·5% oil 25·0% fly ash 68·5% sand	■ Samples were soft and ruptured when compacted	Too wet No further testing

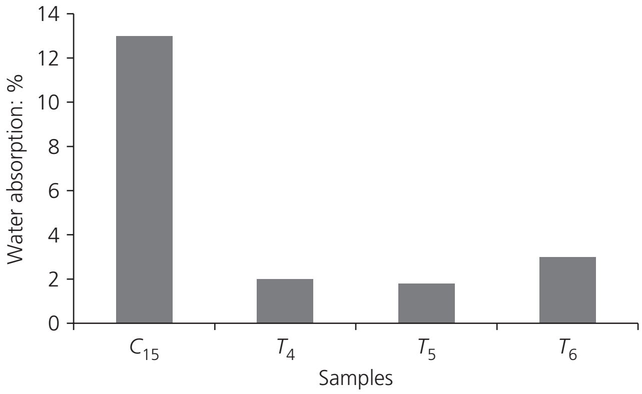

Figure 2. Water absorption comparison for cemented and UEO prototypes samples

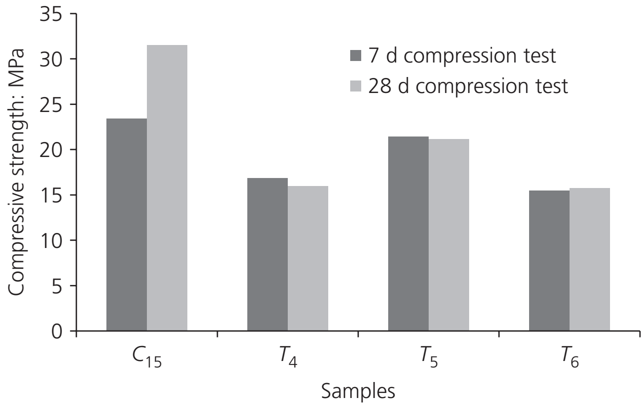

Figure 3. Compressive strength comparison of samples after 7 and 24 d

It is demonstrated from Figure 2 that the water absorption of C_{15} (control samples) was found to be quite high in contrast to the optimised prototypes produced from UEO and aggregate and filler. It can clearly be seen that the water absorption for T_5 prototypes samples was least in comparison with the other samples. Interestingly, water absorption for C_{15} samples was found to be 13%, which is high in comparison with the minimum standard requirements of 10·5% for normal tiles (ASTM C 67-13 (ASTM, 2013); ASTM C 1492-03 (ASTM, 2009)). This indicates that C_{15} mixture is not suitable for the production of normal tiles.

3.5 Compressive strength

Compressive strength is an important test from an industrial point of view since it indicates the ability of the material to resist load. Compressive strength tests for concrete and UEO samples were conducted after 7 and 28 d and the results are presented in Figure 3.

It is revealed from Figure 3 that control sample of concrete (C_{15}) had the highest compressive strength when tested for 7 and 28 d, respectively, in comparison with the UEO samples. Moreover, the compressive strength for C_{15} sample increased considerably after 28 d in comparison with the compressive strength recorded for 7 d. In contrast, T_4, T_5 and T_6 were found to achieve a lower compressive strength compared with the cemented sample. Among the UEO samples, T_5 showed the highest compressive strength of ~21 MPa which is within the standard minimum requirement of 17 MPa for residential concrete (CIP, 2014). Moreover, the compressive strength for T_5 samples remained constant for 7 and 28 d, respectively.

3.6 Flexural strength

Flexural strength or bending strength is the ability of the material to resist load without rupture. Cemented and UEO samples were tested for flexural strength and the results are illustrated in Figure 4. It is observed from Figure 4 that the flexural strength of the cemented samples was on the higher side after 7 and 28 d, respectively. Moreover, the flexural strength increased significantly from 7 to 28 d for the C_{15} samples. However, UEO samples had lower flexural strength

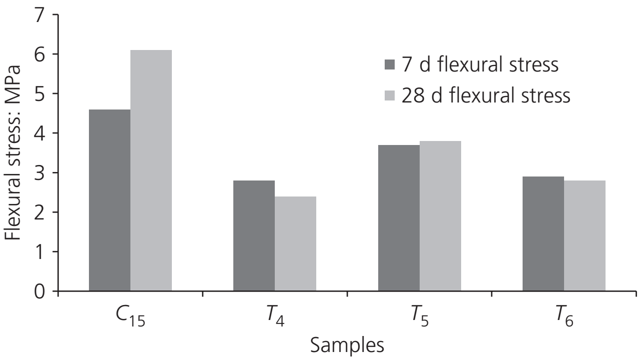

Figure 4. Flexural stress comparison of samples after 7 and 28 d

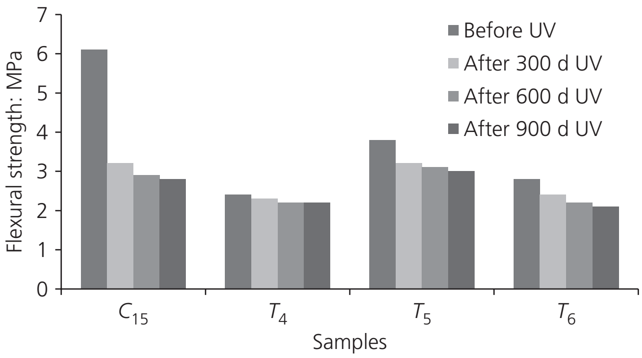

Figure 5. UV test comparison of cemented and UEO samples

and the maximum flexural stress of around 3·5 MPa was achieved by T_5 samples which is within the standard minimum requirement (Lane, 1998). Interestingly, flexural stress calculated for 7 and 28 d for T_5 samples was observed to be in the same range. This is an indication that UEO samples containing 5% (by weight) UEO were properly compacted and had no influence of moisture or ambient environment. The trend of flexural stress for 7 and 28 d was quite similar to that of compressive strength.

3.7 Permeability

One of the important considerations especially in the implementation of roofing tiles is that they should be impermeable. Permeability test was conducted on cemented and UEO samples according to ASTM standards (ASTM C 1167-03 (ASTM, 2012); ASTM C 1492-03 (ASTM, 2009); Johansson, 1995) and the results are indicated in Table 3. Table 3 shows that all five samples of C_{15} and T_5 have passed the permeability test. Thus, T_5 samples are also fulfilling the condition that they can be used as standard roofing tiles (Johansson, 1995).

3.8 UV test

UV light is an indication of the ability of the material to resist accelerated weathering and can have an adverse effect on the material. Cemented and UEO samples were subjected to UV for 300, 600 and 900 d, respectively, and their flexural strengths were determined. Results of the UV test for different time durations are displayed in Figure 5.

Table 3. Permeability test for cemented and UEO samples

	Permeability test				
Sample type	1	2	3	4	5
C_{15}	Pass	Pass	Pass	Pass	Pass
T_4	Fail	Pass	Pass	Fail	Pass
T_5	Pass	Pass	Pass	Pass	Pass
T_6	Pass	Pass	Pass	Fail	Pass

It can be shown from Figure 5 that C_{15} samples were mostly likely to be affected by UV light. Originally, samples of C_{15} had higher flexural strength but after 300 d of exposure to UV, the flexural stress reduced significantly. In contrast, T_5 showed substantial results for UV test, since the flexural stress of T_5 samples did not alter significantly even when subjected to 900 d of UV. Notably, the flexural stress of T_5 samples after 900 d of UV exposure was found to be higher in comparison with the cemented samples of C_{15}. Moreover, the flexural stress for T_5 samples that was achieved was found to be within standard limit for 300, 600 and 900 d of UV, respectively (Lane, 1998). This indicates that accelerated weathering conditions have negligible impact on tiles' samples produced from 5% by weight of UEO.

3.9 Standard UEO tiles

After the optimisation of conditions and initial testing on prototypes, final standard UEO tiles were produced. Standard tiles were investigated for flexural stress, compressive strength, permeability and water absorption, respectively.

3.9.1 Compressive and flexural strength

Compressive and flexural strength for standard UEO tiles produced under optimised conditions is presented in Table 4. Table 4 reveals that the compressive strength for standard UEO tiles was in the range of 17·5–18·3 MPa. The compressive strength that was achieved was found to be well within the standard range for residential concrete tiles (CIP, 2014). Moreover, the flexural stress developed by these tiles was also within the standard limit as indicated in Table 4 (Lane, 1998).

3.9.2 Water absorption

Water absorption calculated for the final UEO tiles is indicated in Figure 6. It is discovered that all the UEO tile samples had low water absorption in comparison with the minimum standard requirements (ASTM C 67-13 (ASTM, 2013); ASTM C 1492-03 (ASTM, 2009)).

3.9.3 Permeability test

A permeability test was conducted on standard UEO tiles according to standard methods and the results are displayed in Table 5. It was found that all the standard UEO tiles have passed the permeability test (Johansson, 1995).

Table 4. Compressive and flexural strength achieved for standard UEO tiles produced at 190°C

Sample number	Compressive strength: MPa	Sample number	Flexural strength: MPa
1	17·5	1	2·9
2	18·1	2	3·2
3	18·2	3	3·2
4	17·7	4	2·9
5	18·3	5	2·9

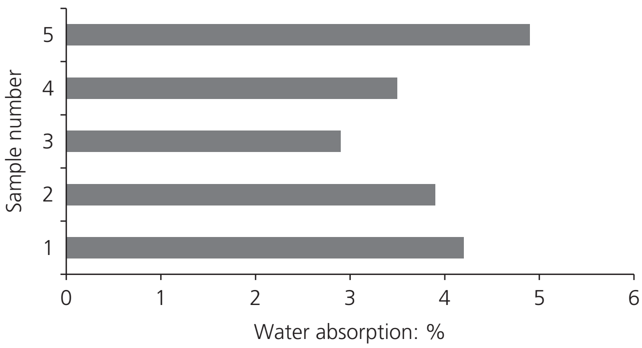

Figure 6. Water absorption percentage for standard UEO tiles

Table 5. Permeability test on standard UEO tiles produced at 190°C and 5 d of curing

Sample number	Filler content: %	Oil content: %	Permeability test
1	25	5	Pass
2	25	5	Pass
3	25	5	Pass
4	25	5	Pass
5	25	5	Pass

3.9.4 Embodied energy and carbon

Since UEO tile samples showed substantial results to be used as a substitute for alternate binders, its environmental aspects were investigated by means of embodied energy and embodied carbon, respectively. Embodied energy and embodied carbon calculated per tile are presented in Table 6.

It is revealed from Table 6 that the embodied energy and embodied carbon of UEO tile were 1·16 MJ/kg and 0·282 kg carbon dioxide equivalent, respectively. Energy comparison of traditional tiles with a UEO tile is presented in Figure 7. It is demonstrated from Figure 7 that embodied energy and embodied carbon in a UEO tile was quite low in comparison with other conventional tiles (Jones and Hammond, 2008). This is because the existing high energy consuming binders were substituted by used or waste engine oil incorporated in aggregates. Since waste materials and aggregates have much lower energy requirements than the raw materials such as clay and cement, the energy requirements of these novel tiles were found to be less in comparison with conventional tiles. This suggests that UEO tiles are more environmentally friendly in comparison

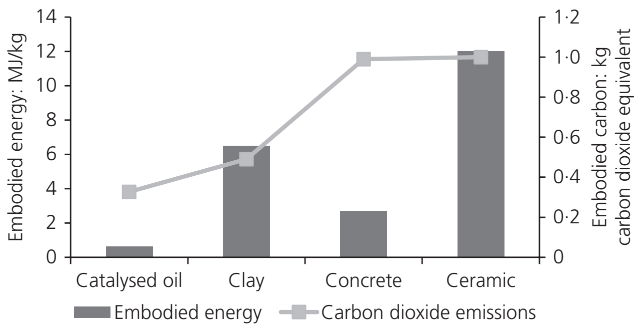

Figure 7. Energy comparison of UEO tile and traditional tiles

Table 6. Embodied energy and embodied carbon per UEO tile

Material	Embodied energy: MJ/kg	Embodied carbon: kg carbon dioxide equivalent	Material required per tile: kg	Total embodied energy per tile: MJ/kg	Total embodied carbon per tile: kg carbon dioxide equivalent
UEO	8	1	0·145	1·16	0·145
Sand	0[a]	0·1	1·353	0	0·135
Fly ash	—	—	—	0	0·002
Total				1·16	0·282

[a]Chani *et al.* (2003)
[b]Leese and Edwards (2012)

Table 7. Cost comparison of cemented and UEO tiles

Cemented tiles				UEO tiles			
Serial number	Description	Rate (RM)	Rate per tile (RM)	Serial number	Description	Rate (RM)	Rate per tile (RM)
1	Cement	400/metric ton	0·170	1	Fly ash	80/metric ton	0·04
2	Sand	80/metric ton	0·102	2	Sand	80/metric ton	0·11
				3	UEO	300/metric ton	0·03
1	Power cost	0·38/kWh	0·06	1	Oven	0·38/kWh	0·15
2	Water	2·07/m^3	Approx. 0·05	2	Mixer	0·38/kWh	0·001
		Total	0·382			Total	0·331

with the traditional tiles and UEO has the potential to replace conventional binders.

3.9.5 Economic evaluation

An economical product is desirable to ensure the feasibility of the process. Fly ash, sand, cement and UEO were procured in Malaysia at a price of RM 80, RM 80, RM 400 and RM 300 (1RM = £0·18) per metric ton, respectively. Electricity and water cost were approximately RM 0·38 per kWh and RM 2·07 per m^3, respectively, in accordance with Tenaga Nasional Berhad and Syarikat Bekalan Air Selangor SDN. BHD, Malaysia. Cost comparison of UEO and cemented tiles is displayed in Table 7. Table 7 shows that the cost in producing a UEO tile is less in comparison with cemented tile. This is an indication that UEO tiles if implemented would be cost effective in comparison with the traditional masonry units.

4. Conclusions

This research reveals that UEO can be used as an alternate binder to replace the conventional masonry units. UEO tile samples having 5% by weight of oil has fulfilled the criterion for conventional concrete or clay tile as it showed impermeability, achieved standard flexural strength and compressive strength and a low percentage of water absorption. Moreover, embodied energy and embodied carbon required by these tiles was discovered to be lower than conventional tiles. However, the embodied energy and embodied carbon calculations were based on many assumptions and further investigation needs to be carried out in this regard. In addition, accelerated weathering conditions have negligible impact on tile samples containing 5% UEO. Remarkably, UEO tiles were found to be economical in comparison with the cemented tiles. This preliminarily research suggests that this novel binder is more environmentally friendly in comparison with traditional binders and has the potential to replace the masonry units. However, since UEO has an ability to include carcinogens and toxic materials, a thorough analysis of the environmental and health impact of UEO as binder is needed before the implementation of use of these tiles. In conclusion, disposal problems of UEO can be overcome by using UEO in the production of building materials.

Acknowledgements

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