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Utilization of Recycled Tiles and Tyres in Stabilization of Soils and Production of Construction Materials

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Abstract

Tile waste is found in several forms including manufacturing slurry, manufacturing dust, and solid pieces from cracked, smashed, and rejected tiles at the construction sites. Worn out tyres that are no longer safe to be used by vehicles are either discarded or burned, adversely impacting natural ecosystems. These wastes are non- degradable and have a direct environmental impact. Poor waste management can lead to hazardous pollution, reduced soil fertility, and increased space consumption at disposal sites. The massive and increasing volume of the tile and tyre wastes calls for recycling of the materials for economical reuse, cleaner production, and greener development. One area for beneficial reuse of these waste materials is the improvement of engineering properties in soft soil. Structures on soft soils may experience several forms of damage due to insufficient bearing capacity and excessive settlement. Hence, soil stabilization is often necessary to ensure that the soft soil can meet the engineering requirements for stability. A comprehensive review of the published literature on the use of recycled tyres and tiles to stabilize and enhance soft soils was carried out. The properties of soft soil-waste mixtures such as liquid limit, plastic limit, plasticity index, compaction behaviour, unconfined compressive strength, and California Bearing Ratio have been presented. When used as partial replacement of cement, sand, and aggregate in concrete, the effect of tyre and tile waste on workability, durability, and compressive strength of the concrete has also been presented. Recycled tiles and tyres have been used with or without any other admixtures to sustainably improve the strength and bearing capacity of soil. The suitability of recycled tiles and tyres in soil stabilization has been discussed with regard to enhancement of strength and reduction of settlement. In addition, the beneficial effects of the recycled tiles and tyres, when they partially replace cement, sand or stone in concrete, have been discussed.

Keywords: *environmental pollution, soil stabilization, recycled tiles, recycled tyre, soft soil*

1. Introduction

Soil stabilization is the physical, mechanical, hydraulic, electrical, or chemical alteration or modification of the main properties of weak soils. It is a technique that has been used since ancient times to provide a solid foundation, strong enough to accommodate the loads imposed by the sub- and super-structure of the buildings, highways and bridges, embankments, and hydraulic structures (Hejazi *et al*., 2012; Kowalski and Starry, 2007). Soil stabilization methods are also employed to provide a good subgrade for existing and future roadway construction projects (Karimi and Ghorbani, 2000; Smekal, 2008, Latifi *et al.*, 2018, 2017a, b, c). Recently, tile and tyre wastes have been introduced as environmentally friendly soil stabilizers to solve the growing problem of waste materials and produce an engineered soil that can withstand heavy loads. In the case of ceramic tiles, the waste amounts to 7% during production process, which causes water, air, and soil pollution if not utilized. The use of ceramic tiles in the stabilization of soft soil will substantially help resolve the aforementioned pollution problems.

2. Soil Stabilization Materials and Methods

2.1 Soft Soils

The term soft soil refers to the soils that have low shear strength, properties that do not meet design requirements, and that exhibit excessive settlement when loaded. Soft soils are not suitable for foundation construction applications due to these poor physical characteristics (Al-Bared and Marto, 2017; Fauzi *et al*., 2016; Rashid *et al*., 2017, Hassan *et al.*, 2017). Soft soil is a general term that constitutes a variety of earthen material with different contents and characteristics. Such soils can be clayey (including marine clays), silty, or organic (such a peat). The problematic behavior of soft soils is based on the type of soil it is composed of. According to Makusa (2012), clay has a large surface area compared to its particle diameter while silt is sensitive to changes in moisture content. Peat and organic soils are very rich in water content (up to 2,000%), and in organics content (up to 75%.). Kazemian *et al.* (2011) state that peat soil is problematic for the construction industry due to its high water and organics content, very low strength, and high compressibility. Aljanabi *et al.* (2013) observed that peat and organic soils have a Standard Penetration Test (SPT) (N) value of 0-5 blows at 300 mm penetration. Many of these soils may also exhibit expansive properties. An expansive soil is a type of soft soil that swells when it gains water and shrinks when it dries out (Baser, 2009). Typically, each of these various soft soil types should be treated before any loading or structure is placed on them or, if that is not possible, replaced entirely.

There are many soil improvement techniques such as use of traditional and non-traditional chemicals, hydrological techniques, and biological methods or a combination of techniques (Fattah *et al.*, 2015). The soil is treated to improve its density by compaction or preloading, to control the pore water pressure by electro-osmosis or dewatering, to increase the bonding of the particles by chemical treatment, or by grouting and reinforcing the soil with geotextiles or fillers (Otoko, 2014). For the purpose of chemical treatment and physical reinforcement, economical, environment-friendly, and sustainable soil additives have recently been more popular (Chang *et al.*, 2016; Rujikiatkamjorn and Indraratna, 2014).

Choosing the best stabilization method for treating weak, loose, or soft soils depends largely on the soil characteristics, purpose of treatment, and the required soil strength (Kazemain and Barghchi, 2012). Various treatment methods have been introduced in the field of geotechnical engineering over the years, which are now considered outdated, such as chemical methods using cement, sodium silicate, and lime as soil stabilizers to obtain the desired physical properties and strength. Amiralian *et al.* (2012) reviewed the use of lime and fly ash as a binder to stabilize the soft soil for construction activities and concluded that these chemical additives enhance all the mechanical and physical characteristics of the soft soil. However, using cement kiln dust and lime in soft soil treatment is not economical and always influences the ecosystems resulting in non-environmentally friendly and unsustainable products. However, the discovery of methods that are environmentally friendly and cost- effective is the main concern of most current studies (Zaliha *et al*., 2013). Roy (2014) used rice husk ash and a small amount of cement in different proportions to stabilize clay soil. The results obtained showed improvement in the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) with significant increases in California Bearing Ratio (CBR) and the Unconfined Compressive Strength (UCS). Roy (2014) reported the optimum value of rice husk ash and cement mixture as 10% and 6%, respectively. Thus, utilizing rice husk ash, which is a waste material produced in high quantities during rice harvesting, in soil stabilization is an economical, environmentally friendly, and sustainable choice.treat soils as reported by Bushra & Robinson (2010). In addition, they found that 15% cement was the optimum value for soft soils.

2.2 Chemical Additives

Many chemical additives are available for use as a soil stabilizer. However, most of them are expensive, non-environmentally friendly, and poisonous. A brief review on chemical additives is presented in the following subsections. Moayedi *et al.* (2012) utilized sodium silicate (Na_2SiO_3) to treat organic soils. The strength of the soil was improved by 220% when 3 mol/L of Na_2SiO_3 was added. In another study conducted in Malaysia by Faizal *et al.* (2015), a commercial sodium silicate liquid-based product called TX85 has been used to treat marine clay. The results of the laboratory tests showed that the additive increased the strength of the untreated soil by 4.5 times in 28 days of curing. Moreover, the additive could improve the soil plasticity. However, sodium silicate was not determined to be an effective chemical additive due to its potential environmental impact.

Cement is considered the oldest method for soil stabilization as it was introduced as soil stabilizer in the 1960s (Makusa, 2013). Tropical peat soil, which is categorized as soft soil, was stabilized using cement and bentonite added together in different percentages. This method resulted in improved soil strength (Deboucha *et al*., 2008). Another study investigated the effect of adding 5% cement, injecting cement grout or 4% gasoline to the expansive soil collected in Iraq. The treatment that used 5% cement resulted in a better strength while the addition of 4% gasoline was found to be the optimum value for this material. Moreover, the internal friction angle was not affected by the treatment because the cement particles had a larger surface area than the soil particles. However, cohesion was slightly affected by the stabilizers due to the exchange of adhesion (Fattah *et al*., 2010). Cement kiln dust and lime were used together to treat the expansive soil in Egypt and the results showed an increase in soil strength and an improvement in all soil properties (Ismaiel, 2013). Cement and lime were used together to stabilize peat soil, which possesses highly compressible characteristics. As the amount of additives increased, UCS and MDD increased and OMC decreased. The efficiency of these two additives was also compared and cement was found to be more effective than lime (Boobathiraja *et al*., 2014). In another study, the strength of inorganic soil used as a subgrade for road construction was improved by treating it with 2% cement (Patel and Mishra, 2014). Bushra & Robinson (2009) treated marine clay, which was excavated to a depth of 1.5 m, with cement. Cement percentages were 10, 15, and 20% of the dry weight of the soil. Treated samples were cured for 28 days under 100, 150, and 200 kPa stress to represent the samples at the depths of 10, 15, and 20 m, respectively. The results showed that 15% cement was the optimum value at which the strength was maximum during the found the optimum value of cement to be 10% but when brown clay was mixed with cement, it reduced to 8.5%. Partial replacement of 1.5% cement by brown clay could be cost effective. The strength of soft soil was significantly improved by this mixture. Although cement was used as a soil stabilizer that strengths the treated soil, it is still considered a chemical additive that has many negative impacts on the surrounding environment and is comparatively expensive.

Magnesium chloride and aluminium chloride have been used to stabilize the swelling properties of the expansive soil. Radhakrishnan *et al.* (2014) used these two additives together with the waste product, fly ash, and found that the application of this combination reduced the free swell and swell pressure while increasing the strength of the soil, which was to be used as a subgrade. When the amount of the combined additive was increased, the swelling properties of the soil decreased and remained constant after reaching a certain concentration. Latifi *et al.* (2016a, b) investigated the behaviour of clayey soils mixed with a magnesium chloride solution. Their results showed a significant improvement in the UCS of the soils, twice as much as the untreated control samples in seven days because of the formation of magnesium silicate hydrate and magnesium aluminate hydrate that filled the pores of the soil. Magnesium chloride was added in different proportions starting from 2% to 10 % with increments of 2%. The optimum value was found to be 8% at which the strength was the highest. In another work by Latifi *et al.* (2015), magnesium chloride was used to treat peat soil, increasing to six times the untreated samples. For this type of soft soil, the optimum additive amount was 6% magnesium chloride which results in the formation of crystalline compounds that contribute to the strength.

Lime was widely adopted as an additive in soft soils many decades ago and many studies were conducted on lime- treated soft soils. Bell (1996) found an optimum value of 4- 6% lime to increase the strength of the clayey soils and clay minerals. The increase in strength was dependent on the amount of water content, temperature, and curing period.

The highest strength was obtained at a water content in excess of the OMC at seven days of curing. Temperature of curing also influenced the strength. When above 30°C, the strength increased dramatically. Furthermore, lime significantly decreased the plasticity of clay soils. Jha and Sivapullaiah (2015) found 6% lime as the optimum value to treat expansive clay. At lower amounts of lime, approximately 4%, with shorter curing period, fabric changes controlled the behavior; while at 6% lime, the behaviour was controlled by the formation of cementitious compounds which in turn decreased the compressibility and increased the strength significantly. Lime injection of underwater marine deposits was studied by Rao and Rajasekaran (1994). The results indicated the formation of cementitious compounds between lime and marine particles that caused a significant increase in the strength and decreased the compressibility of marine clay deposits.

Zhao *et al.* (2014) investigated the use of lime and potassium-and soil suction tests were used to investigate the effect of these types of additives on the swelling behaviour of expansive soil collected from Texas. Laboratory results showed that potassium-based stabilizers can be injected into the soil to form a moisture barrier that can control the swelling pressure effectively while lime showed a total suction drop at the low water content that did not change with the changes in water content. Lime was able to improve the index properties of the soil. Meanwhile, Nikookar *et al.* (2013) found that hydrated lime significantly improved the strength, Atterberg limits, specific gravity, and pH of peat soil collected and tested in Iran. In another study, lime silica fume was used to stabilize the soft soil for square footings before and after construction of the footing. Lime silica fume is a mixture of lime and silica fume that is defined as noncrystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon. The soil underneath and around the square footing was grouted by a slurry of the mixture (4% lime and 5% silica fume). It was found that the soil's bearing capacity and strength was increased in the range of 6.58 - 88% (Fattah, 2016).

Marine clay collected from Iskandar Johor, Malaysia was treated using hydrated lime by Yunus *et al.* (2015). They found that the hydrated lime increased the strength of the soil in a seven-day curing period. Gravina *et al.* (2016) used 3, 5, and 7% lime as a binder to treat Paraguayan Chaco clay and found that higher binder content and overall higher density of the soil led to a higher environmental impact. When the lime content was increased, the strength and stiffness of the soil increased. All these studies suggest that traditional chemical additives increase the strength of the soil, but pose environmental and economic problems. Furthermore, if the sulphate content of soft soil is high, lime starts to deteriorate the strength after a long period of time. This is due to lime forming expandable minerals such as ettringite and thaumasite as reported by Rajasekaran (2005).

2.3 Recycled Additives

Some recycled additives have also been investigated for their effectiveness in improving the soft soil. Fauzi *et al*. (2016) investigated the effect of cut waste plastics together with recycled glass powder on expansive clayey soils. In their study, the engineering properties of the soil, to be used as a subgrade for pavement, were evaluated after adding both waste plastic and powdered glass.

Samples were analyzed using a triaxial test, CBR test, UCS test, and standard compaction test. The percentages of both additives used were 4, 8 and 12% of the weight of the tested soil. The presence of aluminium and silica in the admixture contributed to producing a stabilizing compound that improved the characteristics of the weak soil. Furthermore, the liquid limit and plasticity index values reduced as the percentage of the additives increased and the engineering properties improved when both cut plastic and glass powder were used in the soil admixture.

In addition, cohesion and the friction angle of the soil increased as the additive content increastabilizing the soft soil collected in Turkey and focused on the effect of the waste materials on mitigating the freezing and thawing of soil in seasonally cold climates with severe temperature fluctuations. These changes in temperature make the soil deform during freezing and lose its strength during thawing. The main objective of their research was to determine the suitability of the waste obtained from Green Bayburt Stones (GBS) to enhance soil properties. GBS has many applications including its use in decorating buildings. However, its use always results in a large amount of waste. Indeed, wastage is approximately 60% during the mining and cutting processes, which causes severe environmental problems and health hazards. In Yilmaz *et al.* (2015), GBS was added to the soil in four different percentages; 5, 10, 15, and 20%. The same proportions were also added into the soil together with 6% of lime. The results showed that the UCS of the samples stabilized with a combination of GBS and lime increased more than 1,000% while the UCS of the samples stabilized with GBS only increased only about 20%. Hence, recycled GBS cannot be used independently, but needs a binder, such as lime, to bind the particles with the soil to increase its strength.

Palm Oil Fuel Ash (POFA) is an abundant material produced at palm oil factories and utilizing this material contributes to cleaner production and greener environment. Mujah *et al.* (2015) used POFA obtained from palm oil industry as a filler material to improve the soft peaty soil in Sarawak, Malaysia. Two sizes of ash additives (0.03 mm and 0.012 mm diameter) were added to soft soil for comparison. The results showed that the small particle size was more effective than the larger one in terms of strength and soil stabilization. The shear strength parameters (cohesion and friction angle) were improved by 50-60%. Another study by Pourakbar *et al.* (2015) utilized POFA together with cement to stabilize clayey soil in Johor, Malaysia. At the first stage, the clayey soil was treated with POFA only and then cement and POFA were added to stabilize the soil in a later stage. The ratio of cement-POFA binder was 90-10, 80-20, 70-30, and 60-40%. The binder was added to the soil in three percentages; 5, 10, and 15% of the dry weight of soil. The UCS of the clayey soil treated with POFA was 160 kPa at 28 days curing period. However, the cement-POFA additive sharply increased the strength of the soil. In addition, the plasticity of the soil was reduced by the addition of the cement-POFA binder, which is a good improvement to the soils since soil with high plasticity is considered problematic.

Most studies focused on the use of chemical additives, but they are costly, harmful, and non-environment-friendly. Only a few considered the use of recycled additives. Therefore, the next section discusses the use of some types of recycled material that could be used in soil stabilization, namely recycled tiles and tyre wastes. Treating the soil with tiles and tyre wastes would contribute to clean and sustainable environment and reduce the tendency of the contractors and geotechnical engineers to use chemical additives.Recycled Tyre and

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Tile Wastes and Their Poten-tials

2.4 Recycled Tyre Waste

In the context of this research, recycled tyre waste is described as vehicle tyres that are recycled and reused as a whole in slope stability or as modified shapes (shredded into small pieces) in soil improvement (Marto *et al.*, 2013; Mohamad *et al.*, 2013; Turer, 2011). The volume of tyre waste increases rapidly every year all over the world and massive amounts of tyres are being thrown away without any concern about the consequent hazards, such as supporting the spread of mosquitoes and mosquito-borne diseases because the insects gather in the water that accumulates inside the tyres. In addition, non-recycled tyres have no commercial return (Hazarika and Yasuhara, 2015; Phale, 2005; Torgal *et al.*, 2011). About 80% of tyre waste is being recycled in the United States (Sullivan, 2006). Tyre waste can be used in many civil engineering applications, depending on how it is processed, i.e., shredding and removing reinforcements (Carreon 2006). Tyre rubber can be cut into specific sizes for use as a soil stabilization agent and added to soil in different percentages (Singh and Vinot, 2011). In some cases, nylon and steel are removed from the tyre waste when it is used as a soil additive. Tyre waste has many useful properties when it is used as a subbase under pavements; it is beneficial to the life cycle of the pavement because it can improve drainage and can be compacted and consolidated easily. It is also a lightweight filler (Prasad and Raju, 2009). Yang *et al.* (2002) investigated the mechanical properties of tyre waste and found that its strength is not dependent on the particle size.

Tyre rubber waste is a major environmental problem that affects human beings, animals, and plants. Utilizing this waste product in soft soil treatment and other civil engineering applications will mitigate the environmental problems and result in new products that contribute to protecting the environment.

2.5 Tile Waste

The term tile in this review refers to all types of tiles including ceramic, marble, and stone that are blended or crushed into certain sizes to be used in soil improvement and civil engineering applications. In addition to the wastage from tile factories during the manufacturing process, this review considers the tile waste from construction activities. A significant amount of waste is generated from construction and demolition (C&D) activities (approximately 75% of the total waste produced worldwide), and about 54% of C&D waste is ceramic-based. To give an indication of the magnitude of this problem, a minimum of 400,000 kg and a maximum of 800,000 kg of ceramic tile waste is produced every two weeks in one factory in South Africa and all the waste is dumped in landfills (Zimbili *et al.*, 2014). According to Elçi (2016), the wastage from the production process in the ceramic tiles industry accounts for about 7% of the total production and it

each week (Pelisser *et al.*, 2015). Moreover, Ahmad *et al.* (2014) has produced a list of the most frequently wasted materials in C&D activities in Malaysia. In his list of 15 construction materials, concrete was in the sixth place, followed by tiles in the seventh. According to Anting *et al.* (2014), cracked, broken, or smashed tiles are not used in the construction industry and will finally end up as waste. In fact, ceramic tiles are wasted not just during the construction of new buildings, but also in the renovation of the existing ones.

According to Al Bakri *et al.* (2008), about 30% of the ceramic tiles produced by the tile industry in Malaysia end up as waste products. Moreover, Mahayuddin *et al.* (2008) conducted a study in Ipoh, Malaysia at one of the illegal dumping sites to evaluate the amount of construction waste and the way it is dumped into the environment. They found about 286,500 kg ceramic tiles among the illegally dumped construction waste materials. In general, the tile industry waste is dumped at the nearest point to the factory and by the addition of water during the cutting of the tiles, the waste created is in the form of a liquid slurry that accumulates in water resources and on the ground; thus, adversely affects the surrounding environment. Fig. 1 shows the loss of plants near a tile factory because of the accumulation of tile slurry. This type of tile waste was investigated for use in the production of pavement blocks by mixing it with 15 wt% and 20-30 wt% of cement. The end product, a tile-cement mixture, had the required strength to be used as paving blocks when it

Fig. 1. Accumulation of Tile Slurry Causes Losses of Vegetation (Rana *et al.*, 2016)

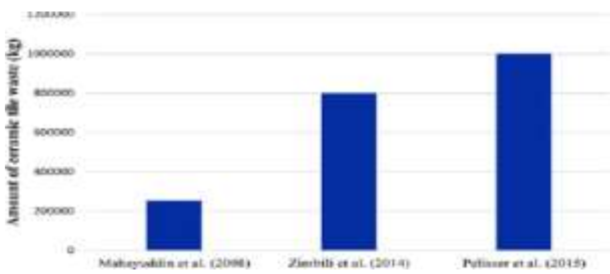

Fig. 2. Amount of Ceramic Tile Wastes Generated from Factories and Construction Sites Reported by Various Researchers from 2008 to 2015 Period of Time

contained 20-30 wt% of cement and was cured for seven days while those containing 15 wt% of cement required a longer curing period (more than 28 days) before they were suitable for use (Wattanasiriwech *et al.*, 2009).

The literature review on the amount of tile waste suggests that reusing this waste in civil engineering applications will reduce the environmental impacts and produce cleaner and stronger products. Fig. 2 depicts the amount of ceramic tile waste reported by various researchers.

3. Utilization of Tyre Waste in Soft Soils and Engineering Materials

The behavior and engineering and mechanical properties of soft soils such as peat and organic soils are difficult to predict or evaluate. Peat soil consists of timber and roots that are formed into the soil under certain conditions while the organic soil is formed from a variety of organic materials (Omar and Jaafar, 2000). Peat soils are also formed in tropical wet areas from vegetation that has been chemically changed and may differ in content from one location to another (Kazemian *et al*., 2011). Construction on these types of soils, which are prevalent in many parts of Malaysia, is impossible and a suitable method of treatment is needed to make them more solid and to increase their load-bearing capacity.

Owing to the increasing number of vehicles on the road and the lack of proper management of the tyre waste, a large amount of tyre waste has been produced in recent years; 57,391,000 kg tyre waste is generated annually in Malaysia alone (Kumar, 2006). Such wastes are suitable candidates to treat peat and organic soils despite some economic challenges. Fig. 3 represents a comparative analysis of the optimum percentage of tyre rubber to be used as a soil additive proposed by various researchers.

3.1 Use of Tyre Waste Alone in Stabilization of Soft Soils

Use of tyre waste in the treatment of soft soils has been investigated by Daud *et al.* (2015), who studied the improvement of the subgrade for the purpose of road construction. The soils used in the study were peat and clay soils collected from Kuala Lumpur, Malaysia. The shredded rubber additive was free of

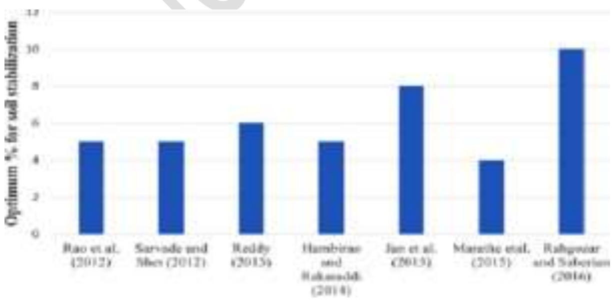

Fig. 3. Optimum Percentage of Tyre Rubber Additive Proposed by Various Researchers for Soil Stabilization

steel and nylon and was cut into pieces ranging from 1 mm to 5 mm in size. Four different percentages of tyre waste (0, 10, 20, and 30%) were added to the peat and clay soils. As for the compaction characteristics, the MDD of both the clay and peat soils decreased as the percentage of shredded rubber increased due to the light weight of the shredded rubber. On the other hand, the OMC increased with the increased percentage of rubber because of the absorption ability of the shredded rubber. Furthermore, the shear strength parameters of the soils were tested using the shear box test. The results showed that the cohesion of the soils increased as the percentage of the additive increased while the angle of friction decreased as the additive percentage increased.

Similarly, Jan *et al.* (2015) investigated the suitability of shredded rubber tyres for the subgrade soil treatment for road construction. The pieces of rubber tyre had a width of 15-25 mm and a length of 30-50 mm while the amount of rubber added to stabilize the soil varied from 4% to 10% in 2% increments. The results of the tests conducted on the soil-tyre mixture showed that OMC and MDD declined as the amount of shredded tyre increased because of the light weight of the shredded tyre rubber. The CBR value of the plain clay soil was 26.01%. The CBR value of the soil-tyre mixture was 66.28% with 8% shredded rubber, which was found to be the optimum value. The improvement in the CBR value was due to the addition of the shredded rubber that decreased the thickness of the pavement and reduced the project costs.

Singh and Mittal (2014) reviewed the materials used to stabilize soft soils and found that scrap tyres could be used as an effective reinforcing material beneath retaining walls, footings, and embankments. Trouzine *et al.* (2012) found that when the amount of scrap tyre added to the treated soil increased, compression and recompression indexes also increased. Suat *et al.* (2007) evaluated the potential of using fiber materials including scrap tyres to strengthen the clayey soil. They proved that these materials are good reinforcement materials that increase the strength and the dynamic behaviour of the clayey soil. Ho *et al.* (2010) treated soft kaolin soils with scrap tyres as additives and cement as a binder to improve the strength and leachability of the soil so that it could be used as a base clay. They found that the UCS values were in the range of 66.5-249.4 kPa after a 28-day curing period. In addition, laterite and chikoko (marine clay) soils were improved by the addition of scrap tyres and cement in different percentages and the UCS value was proportional to the cement percentage. Scrap tyre material can also be used as a reinforcement to substitute deep or raft foundations (Otoko and Pedro, 2014). Marathe *et al.* (2015) studied the stabilization of shedi soil (usually found together with laterite soil) using shredded tyres distributed randomly and cement. The shedi soil could be used as a subgrade for pavement after being improved with an optimum mix of tyre rubber (4%) and cement (2%). Rao *et al.* (2012) conducted research on stabilizing an expansive soil with scrap tyres to increase the CBR value. The CBR value increased with the scrap tyre content until it reached an optimum value of 5%

and then decreased. The maximum CBR value obtained wasof the clayey soil after adding tyre buffing and a small amount of lime and the method increased the CBR value and the strength of the soil. Cosentino (2014) conducted a study on the effect of tyre rubber on the subgrade used for road construction. However, tyre rubber was not suitable to stabilize the subgrade.

The tyre waste can be used as a soil additive to decrease the required thickness of the pavement contributing to a reduction of project costs. The optimum amount of tyre rubber material required to treat soft soils differs from one soil type to another.

3.2 Use of Tyre Waste with Cement, Fly Ash, and Lime in Stabilization of Soft Soils

The large amount of scrap tyres produced and accumulated every day poses a major environmental threat and thus requires immediate and proper action. Many studies attempted to address this problem and several methods were developed to use rubber from tyres in many civil engineering applications. Recently, researchers investigated the use of this recycled material as a reinforcement stabilizer to improve soil strength and performance and minimize settlement (Singh and Mittal, 2014). Hambirao and Rakaraddi (2014) treated black cotton and shedi soils from India using shredded rubber tyre chips as a reinforcing stabilizer and cement as a binding agent. The researchers added shredded rubber tyre obtained from the re- treading industry in two sizes (10-25 mm in length with a thickness of 2-3 mm) to the two types of soil in three different percentages (5, 10, and 15%) and also added cement at 2 and 4% to each mixture. The samples were tested for UCS and CBR. The results showed that UCS increased with the curing period and that a 5% mix of shredded rubber was the optimum value. Moreover, the UCS for black cotton soil before treatment was 15 kPa, with 5% rubber content and 2% cement content it reached 74 kPa and for 5% rubber content and 4% cement content it reached 246 kPa after a 14-day curing period. On the other hand, the UCS of the soil increased from 59.4 kPa to 201 kPa for 2% cement and to 328 kPa for 4% cement. Similarly, CBR increased with the curing period and a 5% admixture of shredded tyre was found to be the optimum value for this parameter. The strength and the bearing capacity were improved not only by the effect of cement, but also by the addition of the optimum percentage of shredded rubber.

Das and Singh (2012) used shredded rubber tyre waste and fly ash as a reinforcing agent and an additive, respectively, to improve the strength of the cohesive soil. Four different percentages of fly ash (0, 20, 35, and 50%) and three different percentages of tyre fiber (0, 5, and 10%) were used to find the optimum value. Triaxial tests were conducted on the original clayey soil, a clayey soil-fly ash mixture, and a clayey soil, fly ash, and tyre rubber mixture. The MDD decreased as the amount of tyre rubber in the mixture was increased to 35%. However, the strength of this mixture decreased more compared to the clayey soil and the clayey soil-fly ash mixture. Moreover, when the tyre rubber was added to the mixture of clayey soil-fly ash, the deformation used crumb rubber powder (CRP), which is made from recycled tyres, as an additive to treat problematic clay in India. The size of the CRP used in their study was 1.18 mm. Since the strength obtained using the CRP alone was not sufficient, ordinary Portland cement and hydrated lime were used together with the CRP to treat the clay. The cement and hydrated lime were added in three different percentages (1, 3, and 5%). First, CRP was added to clay in different amounts (5, 10, 15, 20, and 25% by weight) to determine the optimum value of CRP, which was found to be 5%. Then the optimum mix (5% CRP + clay) was tested after the addition of three different percentages (1, 3, 5%) of cement and lime. Overall, the entire treatment (5% CRP + clay + 5% cement) and (5% CRP + clay + 5% lime) resulted in a 40% increase in the UCS of the clay.

Saberian and Rahgozar (2016) used waste tyre chips and cement to improve peat soil by adding different percentages of these two separate additives. The samples treated with cement exhibited the highest UCS. Reddy (2013) conducted some experiments to obtain the optimum values of rubber tyre and fly ash for use in the stabilization of plastic clay. The strength of the soil reached its maximum value when the optimum value of rubber tyre was 6% and that of fly ash was 25%. More recently, Rahgozar and Saberian (2016) reported the effect of rubber tyre chips to treat soil. With 10% rubber tyre chips, the UCS reached the highest value while with 15% chips the highest ductility was achieved. Bansal *et al.* (2014) studied the stabilization of soil using shredded rubber tyres and found that shredded tyre improved the bearing capacity of the soil 1.78 times the capacity of untreated soil. Jan *et al.* (2015) reviewed the importance of using scrap tyres to treat soil. They observed that road and airfield pavements need soil stabilization to increase the strength and stability. A locally available stabilizing material such as tyre waste should be used so that the construction of these pavements becomes cost-effective.

Sellaf *et al.* (2014) evaluated whether scrap tyre rubber improved the stability of two types of soil. The results showed that the scrap tyre can be used as a reinforcing material to stabilize soil, but it has to be used at a percentage that does not affect the soil compressibility. Ho *et al.* (2011) observed the changes that occurred by adding scrap tyre and cement to kaolin soil. Scrap tyre alone did not result in a significant change in the strength of the soil, but when cement was added, a noticeable increase in strength was achieved. Yoon *et al.* (2006) found that scrap tyre mixed with an equal percentage of sand could be used as an effective fill material for embankments. Lepcha *et al.* (2014) reviewed the use of tyre chips to reinforce soil and observed an increase in strength that help the soil meet design requirements and to reduce the effects of design changes that arise from the presence of weak soils.

In most cases, tyre wastes together with small amounts of chemical agents could significantly improve the Atterberg limits, compressibility, UCS, and the shear strength of the soil. The optimum percentage varied with the type of soil and the chemical agent used.

Use of Tyre Waste in Production of Engineering Materials

Tyre wastes can be utilized in applications other than soil stabilization. They can also be used to replace the aggregates in bituminous pavements. They have been proven to resist water and improve the performance of the pavement by minimizing cracking, reducing sound pollution, and withstanding high temperatures (Baraiya, 2013). Furthermore, tyre wastes can be used to replace the fine aggregates in concrete to produce an economical and sustainable end product. Bravo and Brito (2012) evaluated the effect of aggregates made from scrap tyres on the durability of a concrete mix by replacing the natural aggregates with 5, 10, and 15% of recycled aggregates. Although the strength of the concrete mix was reduced by 50%, concrete shrinkage substantially decreased and water adsorption significantly increased. Similarly, Su *et al.* (2015) studied the effect of using fine aggregates made from used tyres to replace 20% of fine aggregates in concrete. Three different sizes (3, 0.5, and 0.3 mm) of tyre shreds were used and a mixture of them was blended into a finer powder. The tyre-based aggregate increased the workability and water permeability of the concrete. A well-graded tyre aggregate would be efficient when high workability of concrete is needed.

Thomas and Gupta (2016) also studied the efficiency of scrap tyres in replacing natural aggregates in concrete. The strength decreased as the amount of tyre aggregate increased, but the abrasion resistance was better than that achieved by the control mix. Therefore, the concrete mix containing tyre aggregates would serve better than the normal one when brittle behaviour is encountered. Lee (2003) showed that tyre waste together with cement can be utilized in the production of a rubberized geomaterial for use as infill or backfill for earth structures. This geomaterial exhibited excellent performance under both static and dynamic laboratory-based tests. Therefore, employing recycled tyre waste in concrete structures would minimize the use of natural resources in the production of normal concrete mix. Moreover, using rubber tyre material in concrete would reduce the amount of rubber waste (Rahimi *et al*., 2016).

Sadek *et al.* (2015) utilized tyre waste as an aggregate in solid cement bricks used for masonry walls. The size of the chips was 10 mm for coarse and 1.7 mm for fine chips. The results indicated a reduction in the unit weight and compressive strength of bricks with an increased amount of tyre rubber which decreased the weight of the masonry wall and the reinforcement of the foundation. This would surely reduce the cost of construction. Thomas and Gupta (2015) mixed 35% of 0.8-2 mm, 25% of 2-4 mm, and 40% of 0.03 mm size tyre waste. The mixture was used in percentages of 0-20% with an increment of 2.5% to partially substitute fine aggregates in concrete. The percentage of 20% was the optimum value for the rubber tyre to substitute the fine aggregates in concrete in areas where high compressive strength is not important. Treated samples with up to 12.5% tyre rubber showed better resistance to water absorption and carbonation

compared to the control mix. Gupta *et al.* (2016) utilized tyre wastes to partially substitute the sand in concrete. The size of thetyre waste used was 20 mm in length and 2-5 mm in width while the percentages used were 0, 5, 10, 15, 20, and 25% tyre waste together with 0, 5, and 10% silica fume as the partial replacement of cement. The compressive strength of the tyre fibre concrete decreased with the increase in the percentage of tyre fibre and increased with the increase of silica fume. There was a reduction in the static and dynamic modulus of elasticity which indicates more flexibility. Therefore, rubber concrete could be used for buildings subjected to earthquakes and cyclic loading.

In most cases, the partial replacement of the tyre waste in concrete can decrease shrinkage and increase workability, abrasion resistance, and resistance to water absorption and carbonation.

4. Utilization of Tiles Waste in Soft Soils and Engineering Materials

Recently, researchers have started to investigate the use of stabilization methods that can alter and enhance the soil properties in a sustainable, economical, and environmentally friendly way (Chang *et al*., 2016). The conventional method of using chemical additives to improve soil properties is now less favored because most of the chemicals used are harmful to the environment around and within the treated soil. As a result, many studies on soil improvement have been conducted using recycled materials such as powdered tiles (Radhakrishnan *et al*., 2014).

4.1 Use of Ceramic Tiles Waste in Stabilization of Soft Soils

Ceramic powdered tiles are widely used in soft soils as an environmental additive to increase its index and mechanical properties and produce an enhanced soil with cost-effective green technology. Various researchers used ceramic tiles in different percentages to investigate its suitability to treat soft soils and to determine the optimum percentage. Fig. 4 shows a comparative analysis for the optimum percentage of ceramic tiles proposed by researchers to increase the index and mechanical properties of soft soils.

The waste of ceramic tiles during the construction and in the production of the tiles is one of the main environmental problems in

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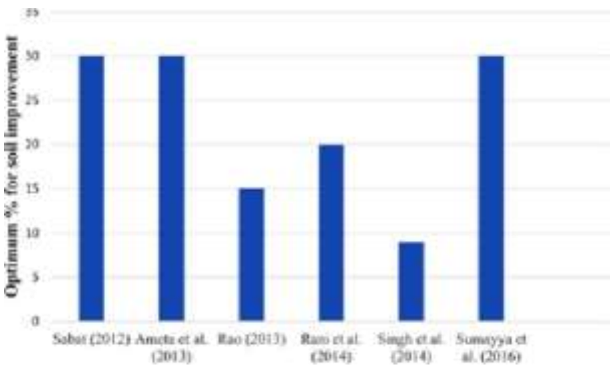

Fig. 4. Optimum Percentage of Ceramic Tiles to Treat Soils Reported by Various Researchers

the world. To utilize the ceramic tile waste, Raghudeep *et al.* (2015) treated black cotton soil with tile wastes to create a good-quality subgrade for road construction. Black cotton soil is usually used as subgrade for pavement, but its engineering characteristics are weak; i.e., when it is wet, it swells and when the water content decreases, it shrinks. The treated black cotton soil gained the required engineering characteristics to be used as a suitable pavement subgrade and the tile waste was utilized for cleaner and green production. Rani *et al.* (2014) used ceramic tile waste to improve expansive soils. A proper treatment is needed for this type of soil to be able to build any infrastructure pavement on top of it. Considering the environmental impacts and the economic value, waste ceramic tiles (1.60% CaO, 19.79% Al_2O_3, and 59.12% silica) were used as an additive in their study to stabilize an expansive soil. Three percentages of the blended tiles (10, 20, and 30%) were added to the expansive soil. Liquid and plastic limit tests, Proctor test, CBR tests, and swelling tests were conducted to determine the optimum percentage of the tile admixture, which was 20%. The tile waste additive could result in a higher performance and strength compared to the untreated expansive soil. Sumayya *et al.* (2016) also used tile wastes to treat an expansive soil and create a good- quality pavement subgrade. The researchers found that with a 30% addition of tile waste, the liquid limit, plastic limit, and OMC decreased while the UCS, shrinkage limit, and MDD increased.

Sabat (2012) studied the effect of the ceramic tile waste on the characteristics of expansive soils collected from construction sites in India. The expansive soil was mixed with ceramic tile dust in proportions ranging from 0 to 30% at the increments of 5%. The liquid and plastic limits decreased as the percentage of ceramic tiles increased. The results of the UCS test revealed an increase in strength from 55 kN/m^2 to 98 kN/m^2 when the percentage of ceramic tiles increased from 0 to 30%. The result of the direct shear strength test showed that the cohesion of the soil decreased from 18 kN/m^2 to 13.5 kN/m^2 when the percentage of ceramic tiles increased up to 30%. On the other hand, the friction angle increased from 13.0º to 17.7º as the percentage of ceramic tiles increased. Kumar *et al.* (2015) reviewed several methods to improve expansive soil treated with ceramic tile dust as a stabilizing agent. The waste ceramic dust was found to be a good additive that improved all of the soil properties such as UCS, liquid limit, plasticity index, CBR, and dry density. This treatment method was both cost-effective and environmentally friendly.

Ameta *et al.* (2013) used ceramic tile wastes to stabilize sand dunes, produce an economical construction material, and solve the problems created by the disposal of ceramic tile waste. Sand dunes are created by the accumulation of sand carried by wind and water flow. Dunes have a low compressive strength and no cohesion. In their study, the sand dune was from a desert in India and the ceramic tiles were from construction sites and manufacturing units in the country. They tested different ceramic particle sizes (4.75, 2.00, 1.18, and 0.43 mm). The laboratory tests used were increments of 5%. The properties of the sand with the admixture improved as the particle size and the percentage of ceramic tile waste increased. Singh *et al.* (2014) used the tile waste together with sand and fly ash to treat clay soil. The admixture proportion of the soil:sand:fly-ash:tile waste was 63:27:10:9, which was the optimum value of compaction characteristics. Similarly, Singh and Sharma (2014) mixed fly ash, ceramic tiles, sand, and jute fibre with local clayey soil to determine the optimum mixture that could be used for geotechnical applications. The results revealed a significant improvement in the clayey soil; its strength was notably increased. Rao (2013) treated marine clay deposits with ceramic tile waste and found that the waste improves all the physical and compaction properties of the soil with a 15% addition of tile waste.

Ceramic tile wastes significantly improve all index properties (liquid limit and plastic limit) and mechanical properties of soft soils (compaction parameters and UCS). As the percentage of ceramic tiles increases, the index and mechanical properties increase until reaching the optimum value. Ceramic tiles also improve the engineering characteristics of soils used as a subgrade for pavement that contribute to the reduction in maintenance costs of untreated soils.

4.2 Use of Ceramic Tiles Waste in Production of Engi-neering Materials

According to Mas *et al*. (2015), ceramic tiles can be used as a replacement material to substitute Portland cement in concrete. Different percentages of ceramic tiles were used to replace various percentages of Portland cement to evaluate the pozzolanic reactivity of the mixtures at different curing ages. The percentage of ceramic tiles ranged from 15 wt% to 50 wt%. Strength was gained over 28- day and 90-day curing periods due to the pozzolanic reaction. Singh and Singla (2015) also used ceramic tile waste to replace 20 mm of natural aggregate in concrete. The compressive strength of the admixture that contained 20% aggregate tiles was the same as that of the natural aggregate for grade 20 concrete. Ceramic and porcelain tiles were used to replace cement and sand to produce concrete blocks for use in pavements. Tiles produced concrete paving blocks that had better strength compared to the control concrete mix. Ceramic tiles replaced 30% of the sand content and porcelain tiles replaced 20% of the cement content in the concrete mix that was cured for 7 and 28 days (Santos *et al*., 2016).

Ceramic tile waste can be utilized in concrete to partially replace cement, aggregate, or sand. Utilizing tiles in concrete will help preserve the natural resources and clean the environment.

4.3 Use of Marble Tiles Waste in Stabilization of Soft Soils

Marble tiles are used in soft soil treatment to fill the gaps between soil particles. Fig. 5 represents the optimum ratio of marble tile waste for soil stabilization by various researchers. Marble waste, which is usually in the form of dust, is considered a global environmental threat due to the high amount of waste produced during the cutting and polishing processes; approximately

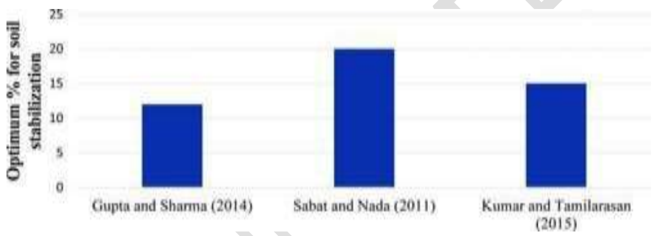

Fig. 5. Optimum Percentage of Marble Tile to Treat Soil Proposed by Researchers

20-30% of marble is wasted (Gencel *et al*., 2012). About 1,400,000 kg of marble dust is produced daily in Turkey (Topçu *et al*., 2009). There have been many attempts to sustainably utilize the marble dust to solve the soil problems for greener production. Tozsin *et al.* (2014) used marble waste to treat an acidic soil in Turkey and marble waste could significantly increase the pH of the soil from 4.71 to 5.88. Gupta and Sharma (2014) treated the black cotton soil using marble dust, fly ash, and sand. The black cotton soil was first mixed with sand, which resulted in an increase in MDD because black cotton particles filled all the spaces around the sand. However, MDD achieved after the addition of fly ash was less than that reported for the sand–black cotton soil mix. Then, the marble dust was added to the mixture in different proportions varying from 8 to 20% but MDD was achieved at 12% marble dust. While the CBR value increased from 2.69% to 8.07% which is about 200%. Singh *et al*. (2014) also investigated the effect of marble dust on the index properties of black cotton soil. With the addition of marble dust, there was a significant improvement in all the index properties. Sivrikaya *et al*. (2014) found that the effect of adding waste stone powder to treat clay soil was similar to that of lime (a chemical additive). When the additive amount was increased, all the physical properties improved and the plasticity index decreased.

Sabat and Nanda (2011) used marble dust together with rice husk ash to stabilize the expansive soil. The best soil stabilization was achieved with 20% marble dust and 10% rice husk ash. The use of marble dust for expansive soil stabilization was also studied by Kumar and Tamilarasan (2015). They found that UCS increased up to 215 kN/m^2 with 15% marble dust. Ali *et al.* (2014) stabilized the expansive soil using marble dust and Bagasse ash that altered all the index properties and the strength of the soil.

Marble tile waste can be used to treat soils either alone or with another additive. Utilizing marble in soil improvement increases the strength of the soil.

5.4 Use of Marble Tiles Waste in Production of Engineer-ing Materials

According to Sadek *et al*. (2016), marble and granite powdered tiles were used as a filler and a binder in self-compacted concrete. Self-compacted concrete have less bleeding or honeycombing, and no vibration is needed in the casting stage. An amount of 50 wt% cement was replaced with marble and granite waste. Granite powder exhibited some pozzolanic activity while the marble powder acted only as a filler. The additives increased the strength, durability, and other physical properties of the mix compared to the control concrete mix. Similar to the use of ceramic tile waste to replace Portland cement, Rana *et al.* (2015) used marble slurry to replace Portland cement in concrete. The optimum value of marble was 10% Portland cement and at this proportion, the mix attained similar strength and workability. According to Careddu *et al.* (2014), the microfine sawdust contained in the marble slurry produced during the marble- cutting process can be used as an effective filler in some industrial products such as rubber and tyres.

André *et al.* (2014) used 20, 50, and 100% marble tile waste as an aggregate in concrete. The results showed no significant differences between the marble aggregate and the conventional primary aggregates in terms of durability. There was a decrease in the compressive strength when the marble aggregates were increased, but the carbonation depth of the concrete made from marble was similar to the reference concrete. Similarly, Uygunoglu *et al.* (2014) used 100% marble waste as an aggregate in the self-compacted concrete that was compared with the concrete made from the limestone aggregate. By replacing the limestone aggregate with marble and recycled concrete aggregate, the workability of the concrete was increased. There was not a significant decrease in the strength when the limestone aggregates were replaced; thus, the marble aggregate could be used as an environmentally friendly aggregate in concrete. Mashaly *et al.* (2016) used 0, 10, 20, 30, and 40% marble sludge in cement composites and in concrete paving units. For both cement composites and concrete paving units, marble sludge improved the physical and mechanical properties of the mixes. A ratio of 20% marble was the optimum value at which the best results were achieved compared to the control mix.

Marble waste utilized in engineering materials can enhance the workability of the concrete and partially replace the aggregates in concrete and cement in paving blocks.

Use of Granite Tiles Waste in Stabilization of Soft Soils Mishra *et al.* (2014) conducted research on black cotton soil using 5% lime and 0-30% granite dust. The granite dust was produced during the cutting of the raw materials in factories. When the granite dust percentage increased, there was a decrease in the liquid and plastic limit and an increase in the shrinkage
limit values.

5.5 Use of Granite Wastes in Production of Engineering Materials

Singh *et al.* (2016a) used 10, 25, 40, 55, and 70% granite dust to replace the sand in concrete. In terms of strength and durability, 25- 40% was the optimum amount of sand to be replaced by the granite waste. At 25% replacement by granite waste, the compressive strength was increased significantly at 0.30 water content. The substitution of granite could continue to up to 40% with increments in strength, but at 0.35-0.40 water content 30, and 50% granite dust to replace sand in a sustainable concrete. The results showed that a 30% addition was the optimum percentage at which the highest compressive strength was achieved, while at 50% addition, the compressive strength was comparable to that of the control mix. The addition of granite waste could increase the packing of the cement aggregate matrix which decreased the free space for water and larger dispersion. This led to a better hydration process that increased the bonding of the concrete.

Singh *et al.* (2016c) also replaced the sand in a sustainable concrete with the granite dust and found that the granite cutting waste was a good additive to the concrete improving the compressive strength, durability, spilt tensile strength, and flexural strength of the concrete. Singh *et al.* (2016d) conducted a study to replace the fine aggregates in concrete with 10, 25, 40, 55, and 70% of granite waste. The optimum percentage of granite was 25% that resulted in a better performance of concrete under the conditions of sulphate attack, carbonation, chloride ion penetration, and elevated temperature because of the physical properties of granite such as surface area.

The granite dust can partially replace sand in concrete and result in higher compressive strength compared to the control mix.

5. Recommendations

Although the current published works deal with using recycled tyre rubber and ceramic, marble, and granite tile wastes to stabilize soft soils for various civil engineering applications, the following are recommended for future research,

1. A combination of powdered tiles and tyre rubber wastes should be assessed for soil stabilization.
2. The possibility of using ceramic and tyre rubber in concrete to replace cement and fine sand, respectively, should be studied.
3. Different microstructural sizes (less than 63 micron) of pow-dered tiles should be assessed in the stabilization of soft soils. The smaller the size of powdered tiles, the better stabi- lizing effect.
4. To evaluate the possibility of tyre waste to replace sand in the production of brick walls. This will produce rubberized bricks that would have better strength and resistance.

6. Conclusions

The amount of recycled ceramic, marble, and stone tile material has a great influence on the strength, index properties, compaction parameters, compressibility, and settlement of soft soils. Similarly, the amount and size of recycled rubber tyres also influence the index and mechanical properties of soft soils. The published papers showed that the recycled rubber tyre could act as a filler material that fill the small voids within the soft soil particles that contribute to better strength of soil while recycled tiles could act as a binder to react with the soil particles and produce new able to influence the workability and strength of concrete and partially replace aggregate or cement to produce new engineering materials. Hence, from the above review of the treatment of soft soils collected from different locations with environmentally friendly additives, the following conclusions can be drawn:

1. Tiles can be used to treat soft soils not only as a filler that increases the strength and physical properties, but also as a binder that reacts chemically with soil components. The results of the published papers proved that tiles induced a

significant improvement of the strength, liquid limit, plastic limit, compaction parameters, compressibility, and CBR of soft soils. Utilizing the vast amounts of tile wastes in soil treatment applications can help reduce waste in the environment, leading to greener construction materials. The conventional methods that use chemical additives to treat soils result in many environmental problems such as the contamination of groundwater. Hence, the tiles can be used to stabilize the soil in an environmentally friendly way.

2. The tyre waste could be used in different forms and sizes to treat weak soils and thus improve all the mechanical and physical properties of the soil. However, shredded rubber tyre can only serve as a filler or a reinforcing agent and, in most cases, cement or lime also is added as a binding agent, which may go into chemical reactions with the treated soil. Therefore, the problem of the accumulated worn out tyres creating a habitat for disease carrying insects and consuming space in waste disposal sites can be tackled by utilizing them in soft soil stabilization.
3. Tile and tyre wastes could also be used in engineering materials with the most benefits found in concrete mixes. The wastes improved the workability of the concrete. In addition, the compressive strength of the concrete was improved when the granite dust substituted the sand. The environmental problems that occurred in areas surrounding marble and granite quarry plants such as the deposition over vegetation and affecting the soil fertility can be solved by using these wastes in improving pavement engineering materials.
4. The use of tile and tyre rubber waste as a soil improvement additive could help to reduce the negative impacts of these materials on the environment by reducing the amount of waste dumped in landfills or directly into the surrounding environment.