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# Portland Cement Treated Soil: Evaluation and Conflict Results

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**Abstract** In spite of soil treatment using Portland cement being well documented, it is hard to find all of the contents related to this topic in one document. This paper aims to provide information inventory about chemical and mechanical changes that take place in soil properties, and the alteration in engineering characteristics which occur in soil - cement mixtures. The mechanism of treatment over time is documented as well. Some conflicted results were detected in literature such as moisture – dry density relationship and dynamic properties of soil treated by cement. The suitability of cement as an additive for different soil types is discussed based on the results which were obtained by different authors. Based on the methodologies followed by laboratory and field studies, the mixture process involves deep and shallow mixing using cement as powder or slurry (grout). Finally, the paper discusses the sustainability of Portland cement as a manufacturing product. Generally, using cement as soil stabilizer induces a significant increase in soil strength, workability, and durability. Permeability and swelling potential are significantly decreased. In addition, a considerable improvement in soil compressibility is achieved for the soil – cement mixture. Negative environment impact is one of the major inherent disadvantages in cement production, where the cement production process is responsible for 5 – 8% of the total anthropogenic $CO_2$ emission. Furthermore, high energy consumption, depletion of resources and weakness against sulfate attack, carbonation and organic materials effects are significant inherent disadvantages in cement-treated soil. So, partial or full replacement of cement by more sustainable materials is recommended.

**Keywords** Soil Stabilization, Treatment Mechanism, Portland Cement, Conflict Results, Negative Environmental Impact

## 1. Introduction

In ancient civilizations, soil was used as construction material since it is a strong and durable material [1]. Moreover, it is cheap and available compared to other materials [2]. From a geotechnical engineering point of view, some soil properties could be inappropriate for some projects, such as soft low strength soil, high compressibility soil, high volume change soil, high gypsum content soil, peat and organic soil and more. Subsequently, stabilization or improvement was needed for such soils and to achieve that and techniques which involved using proper procedures to resolve the problem that the soil was experiencing were applied.

The improvement of soil properties can be achieved mechanically without any additives. Compaction is one of the mechanical methods which comprise of increasing the soil density by using a suitable compacter to increase the packing of the particles and in turn improve soil strength. Moreover, preloading is a mechanism that can be used to decrease the compressibility of soft clay soil.

On the other hand, the improvement of soil can be done by using additives; some of these additives make physical changes in the soil behavior such as fiber, fillers, geogrid and others, whereas some other additives induce a chemical reaction with the soil minerals which lead to the improvement of the engineering properties of the soil [2]. The most popular and traditional chemical stabilizers are lime and cement [3–6]. Both lime and cement stabilized soil involve almost the same mechanisms and effects [7]. The only difference may be that in the case of cement, the cementation products form directly after hydration leading to early soil stabilization. This is because the minerals required for the formation of cementitious products (silica and alumina) are part of its chemical composition, whereas the formation of such products in lime treated soil depends on the silica and alumina provided by the soil minerals [8,9].

Soil stabilization using cement has many advantages. These advantages comprise of increasing strength, durability, and workability. Moreover, it leads to decreasing permeability and improving soil compressibility. However, there are many inherent disadvantages in cement – stabilized soil. One of the most serious disadvantages is a bad impact on the environment caused by the production process of cement. Additionally, it is an energy consumption process. Moreover, soil – cement mixtures are chemically unstable. This paper contains treatment mechanism, and most points of pros and cons of cement-treated soil and it also collects some conflicted results obtained by previous studies.

# 2. Chemical Reaction and Mechanism of Treatment

Two thirds of Portland cement clinker consists of calcium silicates in addition to iron, aluminum and magnesium oxide with some minor compounds, such as gypsum, potassium oxide and sodium oxide. Table 1 represents the important Portland cement components [10].

**Table 1.** Cement components

| Minerals | Formula | Abbreviation |
|---|---|---|
| Tricalcium Silicate | $3CaO.SiO_2$ | C3S |
| Dicalcium Silicate | $2CaO.SiO_2$ | C2S |
| Tricalcium Aluminate | $3CaO.Al_2O_3$ | C3A |
| Tetra Calcium Alumino-Ferrite | $4CaO.Al_2O_3.\ Fe_2O_3$ | C4AF |

According to Umesha et al [10] and Hassan [8], cement-treated soils pass through two phases. Phase one is a primary high−rate reaction of cement components with the pore water of soil. This reaction produces hydrated lime and two cementitious products, hydrated calcium silicate and hydrated calcium aluminates which are responsible for early soil improvement. The chemical reaction can be illustrated in the following chemical equations:

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3\ CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \quad (1)$$

$$2(2CaO.SiO_2) + 4H_2O \rightarrow 3\ CaO.2SiO_2.3H_2O + Ca(OH)_2 \quad (2)$$

$$4CaO\ Al_2O_3\ Fe_2O_3 + 10H_2O + 2Ca(OH)_2 \rightarrow 6\ CaO.Al2O3.Fe_2O_3.12H_2O \quad (3)$$

$$3CaO.Al_2O_3 + 12H_2O + Ca(OH)_2 \rightarrow 3\ CaO.Al_2O_3.Ca(OH)_2.12H_2O \quad (4)$$

$$3CaO.Al_2O_3 + 10H_2O + Ca(OH)_2 \rightarrow 3\ CaO.Al_2O_3.Ca(OH)_2.12H_2O \quad (5)$$

$$3CaO.Al_2O_3 + 10H_2O + CaSO_4.2H_2O \rightarrow 3\ CaO.Al_2O_3.CaSO_4.12H_2O \quad (6)$$

The hydrated products bind the soil particles together as well as the neighboring cement particles. In addition, it fills some soil voids, leading to the formation of a hard skeleton. Cation exchange would take place within a few days which induces flocculation of soil particles. As a long-term reaction, the released hydrated lime induces high alkaline environment leading to dissolution of and reaction with silica and alumina available in soil composition to produce extra (CSH) and (CAH). This reaction represents phase two in cement-treated soil.

# 3. Applications and Advantages of Cement-Treated Soil

Many applications and advantages can be utilized by cement-treated soil using deep or shallow mixing. These advantages can be summarized below:

### 3.1. Water Content–Dry Density Relationship

Sariosseiri and Muhunthan [11] studied the alteration in geotechnical properties of high-water content soil after it was treated with cement. The tested soil samples were from Washington State, USA. The authors observed that the optimum water content increased with the increase of the cement percentage, while maximum dry density suffered from decreasing.

Azadegan et al. [12] tested two types of well-graded granular soils, sand and gravel with the maximum size of 0.9 cm and 1.9 cm respectively. They found that the soil samples stabilized with 4%, 5% and 6% of Portland cement had optimum moisture content greater than that of the raw soil by a significant amount and less maximum dry density. In addition, many other researchers [7,13,14] have obtained the same results from their studies.

Nonetheless, some other researches stated different behavior for cement-treated soil in terms of optimum moisture content – maximum dry density relationship.

Abu Siddique and Rajbongshi [15] evaluated the mechanical properties of low plasticity coastal clayey silty soil obtained from the Chittagong coastal belt of Bangladesh. The obtained soil samples were treated with 1%, 3%, and 5% of Portland cement. After a modified compaction test was carried out on untreated and treated soil samples, they found that while the dosage of cement content increases, the optimum moisture content decreased and the maximum dry density increased.

Deboucha et al. [16] conducted cement stabilization on peat soil with some percentage of bentonite and sand. They found that an increase in maximum dry density was offset by a decrease in optimum water content.

Umesha, et al. [10] used ordinary Portland cement to stabilize soil collected from south of India. The percentages of added cement were 1%, 2%, 3% and 5% by dry unit weight of soil. Compaction characteristics of treated and untreated soil samples were within their experimental program. They demonstrated that the optimum moisture content of treated samples is lower than that of original soil for all cement percentages, while there is a slight increase in the maximum dry density.

Pakbaz and Alipour [17] investigated the alteration of geotechnical properties of natural lean clay after treatment by different content of Portland cement, namely 4%, 6%, 8% and 10% by dry unit weight of soil. The soil samples remolded at various initial water contents (30%, 48% and 70%). Despite the fact that the minimum unit weight of soil samples possessed maximum initial water content and were treated with minimum cement content. They pointed out that the unit weight of all treated soil increased proportionally with cement content and this increment rose with curing time. Horpibulsuk et al. [18] obtained the same results of the increase of maximum dry density. As a result, increase or decrease in the maximum dry density and optimum water content depends on the soil type and preparation conditions.

### 3.2. Decrease Plasticity Index

Generally, a significant reduction in plasticity index is achieved when soil is treated by Portland cement [11]. Al-Zoubi [19] studied the impact of cement addition on some geotechnical properties of high plasticity clay collected from Marj area, Jordon. The adopted cement content ranged from 2% to 25% by dry weight of soil. The result of Atterberg limits tests showed that the liquid limit decreased dramatically in the range of cement contents up to 6%. But, in the range of 6% to 10%, the liquid limit substantially increased. Whereas practically, cement content more than 10% had no effect on the liquid limit. He stated that plastic limit had the same trend, where it decreased until the cement contents reached 10%. The resultant of liquid limit and plastic limit is the plasticity index, where it tends to decrease until the cement contents reach 7% after which the plasticity index rises with cement contents more than 7%.

Sariosseiri and Muhunthan [11] conducted a series of tests on soil modified by Portland cement. Three soil types were obtained from three areas in Washington State, USA. The contents of added cement were 2.5, 5, 7.5, and 10% by soil dry weight. The obtained results refer to an initial increase in liquid limit followed by a decrease with an increasing cement content. Furthermore, there is no noticeable change in the plastic limit which can be deducted. Thus, the plasticity index rises initially and then decreases with an increase in cement percentage. In conclusion, although the liquid limit and plastic limit may be decreased or increased with cement-treated soil, the overall effect is reduction in plasticity index and the soil becoming more workable.

### 3.3. Increase Soil Strength

A lot of researches were conducted on different soil types (fine-grained and coarse-grained soils) to examine the impact of cement treatment on soil strength. Most of them stated that the cement treatment increases the strength of the treated soil. The unconfined compressive strength and the California Bearing Ratio (CBR) tests are usually the tests performed to reflect the soil strength.

Jauberthie et al. [13] stabilized the silt soil obtained from Rance River to show the possibility of using this material as a sub-base for local roads. They used Portland cement, lime, and lime-cement mixtures as stabilized materials. The cement contents were 1.5, 3.0, 4.0, 5.0 and 7.0% by weight of dry soil. They found that there was a significant increase in UCS in the case of cement-treated soil whereas the UCS was 1.7 MPa for 7% cement content and a 7-day curing period. And this value rose to 2.3 MPa in 28-day curing period.

Pakbaz and Alipour [17], whose study was explained previously, carried out the UCS test on the treated samples. The obtained results show that there is a significant rising in UCS values of stabilized soil and this rising changes proportionally with the cement content. The lowest increment in the UCS was for the samples stabilized with minimum cement content (4%) and prepared with maximum initial water content (70%).

Horpibulsuk et al [18] collected a silty clay soil sample to analyze the development of strength after it is treated by cement added with content which ranges from 0 to more than 10% by dry mass of soil. The analysis of strength was from the viewpoint of microstructure. The tested samples were prepared with various initial water contents and cured at different periods. They stated that the UCS increased with the increase of cement content, curing time, and compaction energy. The obtained results show that the maximum strength and stiffness were for cemented soil samples prepared at an initial water content equal to (1.2 OWC).

Moreover, many other researchers have reported the same results stated previously [8,10,20]. The studies above noted that the w/c ratio, initial water content of soil samples, curing time, as well as cement content are the main factors affecting the strength gain of the treated soil. In terms of cohesion, it was reported that the effective cohesion of treated soil increased substantially [21]. But in terms of angle of internal friction, Clough et al. [22] demonstrated that no change could be detected for soil treated by cement. Meanwhile, Uddin et al. [23] stated that the angle of internal friction was increased significantly for cement-treated soil.

### 3.4. Increase Durability

According to Zhang and Tao [24], the durability of treated soil can be evaluated either by strength or mass losses. Parsons and Milburn [25] were interested in the evaluation of the durability of seven different soils treated with cement and three other additives. The classifications of the tested soils were CH, CL, ML, and SM. The obtained results revealed that after 12 cycles of freeze-thaw, the soil-cement combination experienced the least loss in soil mass of not more than 2% to 7%, while the unconfined compression test for the samples treated with cement showed a reduction in strength after freeze-thaw cycles but still possessed significant strength compared with the original soil. For the wet-dry test, the cement showed good results in terms of strength of soil of low clay content. Zhang and Tao [24] evaluated the durability of low plasticity soil treated by six cement dosages. The molding moisture contents were 15.5%, 18.5%, 21.5% and 24.5%. The evaluation depended on three different tests, namely, wet-dry, 7-day UCS, and tube suction tests. The results pointed out that the durability was highly affected by the initial moisture contents of soil samples. Pedarla [26] conducted a laboratory study to investigate the durability of four soils which contained different Montmorillonite contents and were treated with cement as well as lime. A series of wet-dry cycles were applied on soil samples treated with 3% and 6% cement. The results of this study showed that after 3 cycles of wetting/drying, the higher UCS was attributed with samples treated with cement and the value of UCS increased with the increase of cement contents. Aiban, et al. [27] carried out a durability test for cement-treated marl soil. Durability test based on weight loss was adopted using two different procedures, namely ASTM D 559 and slake durability test. The researchers concluded that a percentage of 4% of cement was enough to obtain durable marl – cement mixture. This conclusion was obtained by many other authors[28].

### 3.5. Decrease Swell Potential and Volume Change

Al-Rawas et al. [7] studied the ability of cement and some other additives to reduce the swelling potential of expensive soil samples collected from northern Oman. The prepared samples had been done with their natural water contents and dry density and combined with a cement content of (3%, 6% and 9% by dry unit weight of soil. The results of the study revealed that the swelling percentage decreased from 9.39% to 5.43, 4.57, and 3.67 for soil samples treated by 3%, 6% and 9% of cement content respectively.

As explained above, the study of Al-Zoubi [19] contains the preparation of two soil samples with an initial water content of 15% and 17% and the treatment with a cement of dosage ranged from 2% to 25%. After the free swelling test was conducted, he found that the percentages of free swellings lowered dramatically with cement contents up to 4%, but in the range of 4% to 6% of cement contents, the free swellings essentially increased. Moreover, the free swelling has decreased again for the samples treated by more than 6 % of cement. The decreasing in the free swelling at this stage is more steadily than that of less than 4% of cement content.

The swell test conducted by Parsons and Milburn [25] on the soil-cement samples compacted to 92% of the maximum dry density and showed that the volume changed over a 4-day period and decreased compared with the original soil.

### 3.6. Effect on Permeability

The study of Parsons and Milburn [25] explained above showed a decline in permeability values for samples combined with cement and prepared with optimum water content and cured for a 7-day period.

Bahar et al. [29] was interested in improving sandy clay soil by ordinary Portland cement to use as construction material. The cement contents ranged from 4% to 20% by dry mass of the soil. The result of the falling head test demonstrated that the hydraulic conductivity declined significantly with the cement contents.

Cement whose contents ranged from 25 to 150 kg/m$^3$ was used by Hassan [8] to treat three different clayey soils. The permeability test was among the conducted tests using a flexible wall permeameter. It was pointed out that the permeability lowering of cemented clay was attributed to the amount of cement and after curing dry density.

The study of Sasanian [20] contained the microstructure analysis of three clayey soils stabilized by two types of binders. Ordinary Portland cement was one of the two binders used in this study. The hydraulic conductivity of cemented soil samples was measured using the oedometer test. The outcome of this test showed that the specimens stabilized with 2% of cement had almost the same permeability of untreated soil. But the hydraulic conductivity declined substantially for the specimens treated with a cement dosage of 4.2% and 8.7%.

### 3.7. Effect on Compressibility

The study of Pakbaz and Alipour [17] involved a consolidation test on the treated soil samples. They demonstrated that the compression index of the pre-consolidation pressure increased with the increase of the cement contents. They noted that the pre-consolidation was affected adversely by the initial water content.

Ho and Chan [30] carried out a comprehensive study to investigate the impact of cement on the behavior of Malaysian soft clay collected from a depth of 1.5m. The nine prepared specimens were treated by cement contents which varied from 0% to 10% with moisture contents of 70%. The results of the oedometer test showed that the compression index (Cc) as well as recompression index (Cr) declined over the curing period and with an increasing cement content.

A series of one-dimensional consolidation tests were conducted by Feng et al. [9] on soft mud specimens before and after treated by 6% of cement. From the obtained results, they found that the pre-consolidation pressure and the coefficient of the consolidation increased for the treated soil, and they also noticed a reduction in secondary compression index.

### 3.6. Effect on Dynamic Properties

It found that the soil dynamic response could be enhanced by adding a low percentage of cement to sandy and silty clay soil, whereas the dynamic shear modulus and damping increased significantly [31]. Nevertheless, other researchers found the opposite result regarding the damping ratio, where it diminished with the cementation effect [32]. Pantazopoulos and Atmatzidis [33] pointed out that the grout w/c ratio had the dominant impact on the dynamic properties of the sand soil. On the other hand, Type and fineness of the cement played a secondary role. According to Tsai and Ni [34], an adverse relationship was found between the shear modulus of the cement-treated soil and the shearing strain. However, the damping ratio correlated positively with the shearing strain. The clay soil modified by cement and subjected to freeze-thaw cycles showed noticeable improvement in dynamic response and resilient modulus [35]. Shaking table and pullout tests were conducted on pure sand and clay soils and then on cement-treated versions of them. The outcome of this study showed that the pullout load decreased by adding only a maximum of 5% of cement. Moreover, the stability of the soil-cement mixture improved significantly compared to the pure soil when exposed to an earthquake shake [36]. Many studies dealt with the same context such as [37].

## 4. Disadvantages Inherent Cement Treated Soil

### 4.1. Sulfate Attack and Carbonation

According to the oxide analysis, Portland cement comprises more than 60% of CaO, and the cement past contains almost 25% by volume of $Ca(OH)_2$ [38]. Therefore, lime and cement have substantial similarities in terms of chemical reactions and products [39]. Consequently and as in lime treated soil, the presence of sulfate constitutes an undesirable and deleterious component in cement-treated soil because of the large potential to form calcium–aluminum–sulfate (ettringite) [40]. Sherwood [41] reported that the ettringite formation caused swelling and induced strength reduction in cement – treated soil. Yong and Ouhadi, [42] recommended that careful action should be taken for cement and lime treated sulfate soil and that the same measures aforementioned in lime treated sulfate soil should be conservative to minimize the effect of ettringite formation in soil treated by cement.

Bagonza et al. [43] stated that carbonation would occur in cement-treated soil when lime released from cement hydration reacts with atmospheric carbon dioxide leading to form ($CaCO_3$). Calcium carbonate would also be produced from the chemical reaction of hydrated calcium silicates (CSH) and/or hydrated calcium aluminates (CAH) with $CO_2$ as illustrated in the following equation [44]:

$$CSH + CAH + CO_2 \rightarrow CACO_3 + SiO_2 + Al_2O_3 + H_2O \quad (7)$$

All the previous researchers stated that the carbonation of Portland cement – treated soil inhibits the strength gain for stabilized soil and increases soil plasticity. They recommended that avoiding compaction slowness and achieved maximum density determines the entry of carbon dioxide and the effect of carbonation.

### 4.2. Effects of Organic Materials on the Chemical Reactions

Hampton and Edil, [45] reported that cement-treated soil is vulnerable to organic material effects represented by hindering the chemical reaction of cementitious formation. Tremblay et al. [46] found that soil contains organic acids which have a pore solution of pH less than 9 which inhibits the cementing reaction from taking place when treated with cement, while cement-treated soil contains non-miscible hydrocarbons and the oil is successfully strengthened but with a long curing time because these organic materials are inclined to coat cement grains leading to a delay in hydration. Accordingly, the quantity and nature of organic materials should be considered when cement treats organic soil. Hassan [8] pointed out that soil containing organic matter consumes a large cement quantity to obtain considerable treatment. Pousette et al. [47] reported that a comprehensive laboratory study is very important to choose an appropriate binder type and content for organic soil treatment.

### 4.3. Disadvantages Inherent Portland Cement

#### 4.3.1. Negative Environmental Impact

Global warming, as it is an environmental problem, is considered the most dangerous problem which has menaced the planet [48]. The carbon dioxide ($CO_2$) emission is one of the main greenhouse gases that cause global warming [49]. Global warming may lead to some dangerous phenomena, i.e., extinction of some plant and animal species, radical climate such as tropical cyclones, and a rising sea level [50]. The increase of $CO_2$ emission is associated with human activities. One of these activities responsible for $CO_2$ emission is the cement industry [51]. The production of one ton of cement emits approximately one ton of $CO_2$ [52]. Therefore, the cement industry is responsible for about 10% of the total $CO_2$ emission caused by human activities [53]. $CO_2$ emission in the cement industry is caused by four main sources, i.e., decarbonation of limestone, burning fossil fuels, transportation, and electricity. The contribution of each source is illustrated in Figure 1.

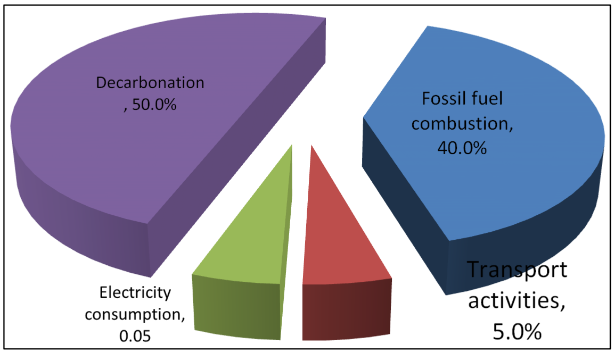


**Figure 1.** Sources of $CO_2$ emission in the cement industry, source of data is [55]

The decarbonation and fossil fuel combustion have the major contribution in the $CO_2$ emission. Therefore, the cement industry contributes to about 5% to 8% of total $CO_2$ emission caused by human activities [54]. Moreover, what aggravates the problem is that the cement industry is growing at an annual constant. Figure 2 presents the distribution of the cement industry worldwide. It is clear from Figure 2 that China is the top cement producer. After China, India came in the second rank. Figure 3 illustrates the growth of the cement industry over the years. The world cement production in 2003 was 1.86 billion tons. Whilst, this production grew to 3.7 billion tons in 2012. The cement production is expected to be increased to 5 billion tons in 2030 [54]. As a result of the cement production growing, the $CO_2$ emission is expected to increase as well. Figure 4 shows the increment in the $CO_2$ emission up to 2050 [55]. This expectation was made in the case of the absence of the necessary actions to reduce the $CO_2$ emission. In addition to the above, cement manufacturing leads to depletion to the natural resources [53].

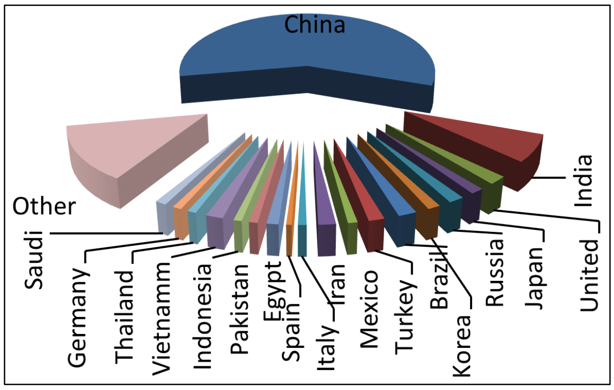


**Figure 2.** World cement production, source of data is [56]

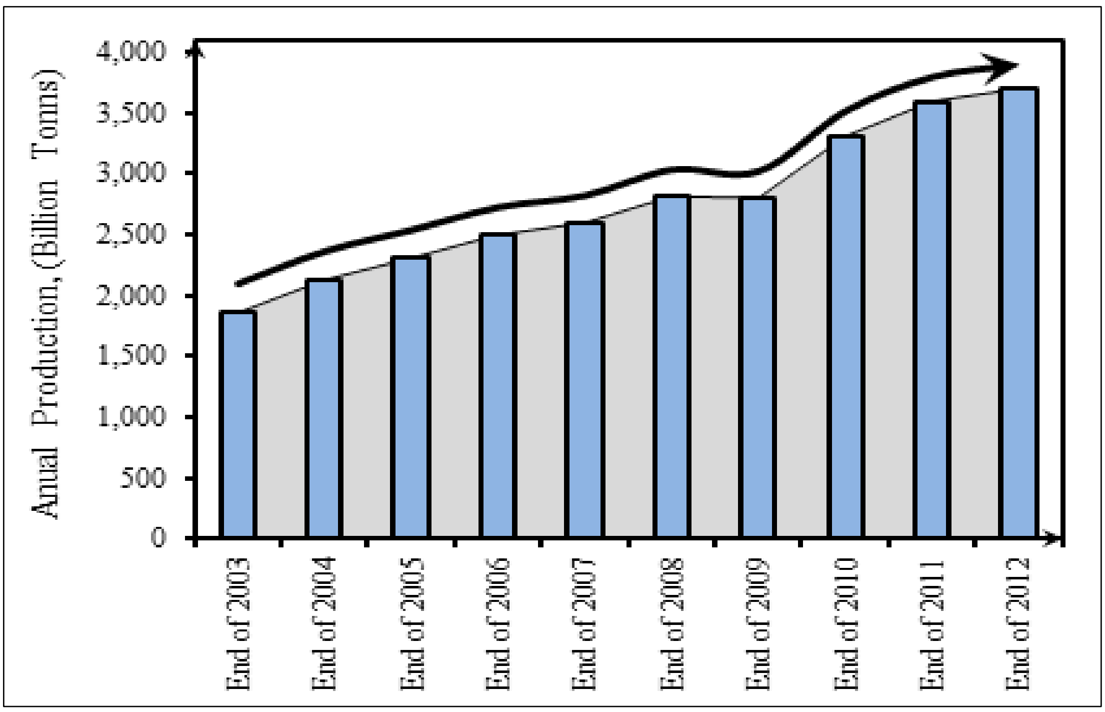


**Figure 3.** Growing of cement industry, source of data is [57]

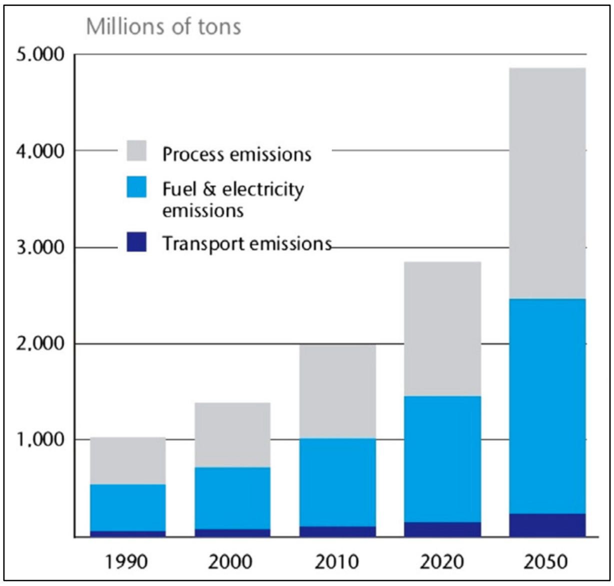


**Figure 4.** $CO_2$ emission (million tons) for global cement industry [58]

4.3.2. Energy Intensive

Since the clinker burning occurs at a temperature not less than 1450 or 1500º C [54,59], cement manufacturing is considered a high energy consumption industry [60]. It consumes 3% of worldwide energy and 1.5% of worldwide electricity production. Therefore, the energy forms 30% to 50% of the cost of cement manufacturing [59]. The producing countries consume a very large amount of the overall production of energy in the cement industry. China – as the largest producer for cement (Figure 2) – consumed 7.1% of the overall energy consumption and 10.1% of the consumption energy in the industry sector [61]. Meanwhile, in India – the second largest producing country in the world – 13.5% of the total industrial energy was consumed by the cement production in 2006-2007 [62]. On the other hand, the increase in the cost of fuel, as its sources are being depleted, will have increased the cement price twofold by 2030 [63].

# 5. Case Study

A case study was carried out by Aiban, et al. [27] to stabilize marl soil which represents the majority of the subgrade soils of the roads in eastern Saudi Arabia. The laboratory results showed that the strength of the marl soil in this area has high sensitivity to moisture contents, which means that the soil strength experienced a considerable amount of strength reduction once the moisture content was increased. Additionally, the above study proposed using cement to solve this problem and hence, a laboratory and field program was adopted to investigate the efficiency of the proposed solution. Moreover, based on the unconfined compression test, CBR test and durability test, 4.0% of sulphate resistant (Type V) Portland cement was used; the laboratory results showed a significant increase in the soil performance after it was treated by 4.0% of cement. On the other hand, four road sections were chosen for the application of the results of the laboratory tests; the base layers of two of these sections were reconstructed using the original marl soil whilst the base layers of the others were built using marl – 4% of cement. All sections had the same base thickness with the same length and were all exposed to the same traffic load and environmental conditions. Subsequently, with four years of continuous observation and evaluation, it was noted that the sections with original soil showed different forms of damage, whereas the section that was built by stabilized marl soil experienced excellent performance without any signs of deterioration.

# 6. Conclusions

Soil stabilization using ordinary Portland cement leads to a significant improvement in soil engineering characteristics in both short and long terms. The mechanism of treatment involves binding the soil particles as the hydration of soil – cement mixture begins in the presence of water by the formation of CSH and CAH. At the same time, flocculation and agglomeration of soil particles take place by $Ca^{+2}$ ions after releasing a considerable amount of hydrated lime. As long-term stabilization, the high alkaline environment induces dissolution of soil silica and alumina leading to the reaction with the free $Ca^{+2}$ and further formation of CSH and CAH.

These processes cause a significant increase in soil strength, workability, and durability in addition to a considerable improvement in soil compressibility. Moreover, a noticeable reduction in swelling potential is achieved as well.

It was found that some results are conflicted with each other such as permeability, Dynamic Properties and dry density – moisture content relationship.

On the other hand, there are significant inherent disadvantages when using cement as soil stabilizer. The first disadvantage is the negative impact on the environment. Cement-stabilized soil is weak against aggressive chemical attack (sulfate attack) and carbonation reaction. Ettringite formation due to sulfate attack and calcium carbonate formation due to $CO_2$ absorption hinder the strength gain of the soil – cement mixture. Furthermore, cement treated soil is vulnerable to organic materials effects.

The cement production process causes $CO_2$ emission. $CO_2$ is one of the dangerous greenhouse gases which cause global warming in the environment. Moreover, cement production is responsible for 5% to 8 % of total anthropogenic $CO_2$ emission. Secondly, cement production is a high energy consumption process. In addition, it leads to depletion of resources.

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