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A Decision Support System for Ground Improvement Projects Using Gypsum Waste
Case Study: Embankments Construction in Japan

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Abstract:

This paper introduces a multi criteria decision making model to support the decision makers who work in the ground improvement projects such as embankments construction using stabilizer materials. The use of cement as a stabilizer material in embankments construction has a long history while the application of recycled gypsum in cooperation with cement as a stabilizer material is recently introduced in Japan. Four criteria and many factors are identified to compare the two stabilizer materials, cement only or gypsum-cement mixture, for the purpose of choosing one of them. The four criteria include: saving in cost, project scope achievement, durability, and geo-environmental impacts. The proposed model, which depends on the Analytic Hierarchy Process as a multi-criteria analysis method, is developed based on cost calculations, expert knowledge for achieving scope, and laboratory test results for durability and geo-environmental properties for each stabilizer material. It is applied on a real case study for embankments construction project in Japan. Based on the results of model application on the investigated case study, a decision introduced to Japanese construction market is that using gypsum-cement mixture as a stabilizer in ground improvement projects is better than using cement only by almost 50%. This result supports the application of recycled gypsum, produced from gypsum wastes, as a stabilizer in ground improvement projects to achieve the stability of society by reducing the quantities of wastes, meet sound environment, and reduce the cost of construction. Besides, the paper discusses in details the factors and reasons which have different effects on the two stabilizer materials and control the decision making.

Keywords: Ground improvement; Decision making; Embankment construction; Gypsum waste; Gypsum-cement stabilizer; Multi-criteria analysis

List of abbreviations:

GWPB: gypsum waste plasterboard

C: Cement only

GCM: Gypsum-Cement Mixture

AHP: Analytic Hierarchy Process

1. Introduction

Solid waste management is a serious problem all over the world due to the huge amount of waste materials produced and increased annually, especially in the developed countries such as USA, Europe and Japan. Therefore nowadays, extensive efforts have been directed to protect the environment by using waste materials as alternatives in civil engineering projects. The use of waste materials with minimum processing in construction projects has many environmental benefits in addition to saving the cost of their elimination, recycling, and disposing. Gypsum Waste Plasterboard (GWPB) is considered one example of these waste materials. It is a serious problem especially in a wet environment due to the emission of hydrogen sulfide gas, which is not friendly with the environment and increases the fluorine solubility up to the permitted limits, which may cause soil contamination (Kamei & Horai 2008; Ahmed *et al.* 2011a). Gypsum plasterboard is made from gypsum sheets, which is reinforced with synthetics fibers and covered in both sides by papers. In Japan, plasterboards, drywalls, and wallboards are considered the main materials for wall construction that used in buildings. As a result, large quantities of GWPB are produced annually in Japan, approximately 1.7 million tons, during the three stages of production, construction and demolition (Ahmed *et al.* 2011b). Disposing of GWPB in landfill sites in Japan faces many challenges due to the high cost and restricted environmental regulations. Consequently, it is essential to find an alternative way for using GWPB instead of disposing in landfills to meet sound environment and reduce the cost of disposing in landfill sites. For that, GWPB management is considered a burning issue in Japan due to the controlled waste material sites is full. The production of recycled gypsum from GWPB is considered the best way to solve the problem of gypsum wastes instead of their disposing in landfill sites. Recycled gypsum is produced from GWPB by heating under specified temperature for a certain time. The production of recycled gypsum from GWPB was provided in previous works in details (Kamei *et al.* 2007; Kamei & Shuku 2007; Ahmed *et al.* 2011b). The use of recycled gypsum as a stabilizer material in ground improvement projects such as embankment and road construction is introduced in Japan in 2007 (Kamei *et al.* 2007; Kamei & Shuku 2007).

Previous studies dealt with the use of recycled gypsum, derived from gypsum wastes, as a stabilizer in Japan and proved positive results in ground improvement projects (Kamei *et al.* 2007; Kamei *et al.* 2011; Kamei *et al.* 2013a; Ahmed *et al.* 2011a;b). Although this positive results, there many challenges that related to durability and environmental impacts. The durability of ground improvement projects due to the incorporation of recycled gypsum as a stabilizer is a serious problem especially in a wet environment because gypsum is a soluble material in water. As the solubility of gypsum has a negative effect on the durability, also it has a negative effect on the environment. This is due to the emission of the hydrogen sulfide gas and the solubility of harmful substances such as fluorine, boron and hexavalent chromium are more than the standards when recycled gypsum introduced in ground improvement (Kamei & Horai 2008; Ahmed *et al.* 2011a). Previous studies introduced a solution to overcome the associated problems of durability and environmental impacts when recycled gypsum introduced in ground improvement projects (Kamei *et al.* 2011; Ahmed & Ugai 2011; Kamei *et al.* 2013b). This was done by the development of solidification technique based on cement, fly ash, slag and blast furnace cement and reasonable results were obtained for durability and environmental properties. While, decision making to select recycled gypsum, derived from gypsum wastes, as a stabilizer in ground improvement projects instead of traditional materials is not investigated in literature up to author's knowledge. So, a supported decision making for using recycled gypsum instead of traditional stabilizer materials such as cement is needed.

Therefore, this paper deals with the decision making for the application of recycled gypsum, produced from gypsum wastes, as a stabilizer in embankments construction projects in Japan. As a result of increasing the incorporation of waste and recycled materials as alternative materials in ground improvement projects, it is essential to study the decision making for using such materials instead of traditional materials to meet the satisfaction of clients and contactors. In fact, this study is important in order to support the use of recycled gypsum, produced from gypsum wastes, as a stabilizer in construction market in Japan to fulfill the standards. Specifically, this study deals with four criteria along with their factors to build a decision for using recycled gypsum, produced from gypsum wastes, as a stabilizer in embankments construction instead of using cement. These criteria are including saving in cost, project scope achievement, durability, and geo-environmental impacts. Besides, the main research objectives in this paper are: (1) Identifying multi criteria include sources, activities, and all factors affecting the multi criteria that control the choice of Cement only (C) or Gypsum-Cement Mixture (GCM) as a stabilizer material; (2) Designing a multi-criteria decision support model using Analytic Hierarchy Process (AHP) to ease the material selection process; (3) Testing the designated model using data from an actual case study; and (4) discussing in details the factors and reasons which have different effects on the two stabilizer materials and control the decision making.

2. Decision Making in Construction Projects

Decision is an irrevocable allocation of resources (Howard 1966). The problem of decision makers is that their decision should consider many factors affecting more than one criterion for each project. The criteria may be incompatible due to overlapping of advantages and disadvantages of them. Many researches tackled decision making problems in construction industry for many purposes such as comparing and selecting projects, contractors, bids, methods of construction, planning alternatives and suitable building materials.

In project selection, Dikmen *et al.* (2007) presented a model to show how project selection process could be done by regarding both quantitative and qualitative criteria. Ravanshadnia *et al.* (2010) proposed a construction project selection model that used a fuzzy multi-attribute decision making method to identify whether one should offer or not offer a tender and to select a project by considering probable policies.

Other examples used the decision making systems in construction projects such as (Ning *et al*. 2011) who used decision making system to solve dynamic multi-objective and unequal-area construction site layout planning. Nieto-Morote & Ruz-Vila (2012) presented a multi-criteria decision problem based on Fuzzy Set Theory, which uses linguistic assessment or exact assessment of performance of the contractors on qualitative or quantitative criterion. Ebrahimnejad *et al*. (2012) used a decision making system for a construction project problem under multiple criteria in a fuzzy environment. Yao-Chen & Shih-Tong (2013) employs a fuzzy multiple criteria decision making approach to systematically assess risk for a metropolitan construction project. A Management Information System to support decision making on construction projects across all management levels within the owner and the contractor organizations is introduced by Scherer & Schapke (2011).

Selection of suitable building material options can be a very complex process, being influenced and determined by numerous preconditions, decisions, and considerations (Wastiels & Wouters 2008). Van Kesteren, *et al*. (2005) presented a material selection consideration model where product-personality, use, function, material characteristics, shape, and manufacturing processes are represented as the elements that are considered by the designer during the material selection process. Rahman *et al*. (2008) developed a multi criteria decision making model to solve combinational problems associated with the material selection process considering the life-cycle of materials and technologies at the least cost. Knoeri *et al*. (2011) analyzed construction stakeholders' behavior, and decision making regarding recycled mineral construction materials for the construction material market in Switzerland.

3. Data Collection Strategy

The brainstorming is one of the most common identification techniques for data collection in construction industry. To satisfy the research objectives, two brainstorming sessions are organized at Gunma University, Graduate School of Engineering. First session is conducted to identify criteria concerns ground improvement using C or GCM, factors affecting them, and the execution steps. This session was carried out with two professors, three research team members and two project manager, with practical experience in executing and supervising these types of projects. Second session will be explained later in Case Study Description and Model Application section. As a result from first session, four criteria and twenty-six factors affecting them were identified as having impacts from a theoretical perspective and become the theoretical foundation for the project. The results from the brainstorming session was designed to address the decision making process for materials selection to stabilize embankment construction projects. Table 1 shows the identified four criteria and factors affecting them.

Four activities are defined for execution include: 1) Excavation activity which includes excavation and transferring soil to mixing area; 2) Mixing activity which means stabilizing soil or mixing material with soil; 3)Transferring activity which means transferring stabilized soil to its original place; and finally 4) Compaction activity which concerns compacting the stabilized soil. In order to define whether information gathered is cultural bounded or dependent on the respondents' background, other information, possibly, influencing their opinions was also collected.

Table 1. Brief description for the identified four criteria and factors affecting them

Criterion 1: Saving in cost (due to the used materials)
1 - Cost of 1m^2 for execution in the two cases
2 - Saving land price used in landfill sites which needed to dispose Gypsum wastes
3 - Cost differences due to design or borings or any other elements in the two cases
Criterion 2: project scope achievement
4 - Limits for the use of materials in the two cases
5 - Need for administrative approval for the use of materials
6 - Difficulties to achieve the Geo-environmental properties during execution
7 - Availability of materials in the market
8 - Need special equipments or method of construction technology for activities execution (for example drilling-mixing-transferring -compaction)
9 - Need for special workers or crews
10 - Influence of the surrounding environment, for example, the proximity of Agriculture - industry - water resource - housing
11 - Need more efforts for supervising during execution
12 - Time difference for completing activities (mixing , transfer , or compaction)
13 - Cost difference due activities execution. (not due to materials)
14 - Influence of type of soil or other mechanical soil properties such as water content on activities execution
15 - Depth effect of soil layer to be stabilized on activities such as excavation and mixing
16 - Effect of weather conditions such as rain or wind on the activities or on the materials
17 - Dangerous materials emerging during mixing or transferring activities to workers health
18 - Poor achievement to the desired soil properties such as stress or compaction
19 - Rework for some activities such as compaction
Criterion 3: Durability
20 - The durability on the long run
21 - Effect of weather conditions on the durability
22 - Effect of landslides and earthquakes on the durability
23 - Other problems may affect the durability on the long run
Criterion 4: Geo- Environmental Impacts
24 - The advantage of using Gypsum waste in stabilizing soil instead of disposal
25 - Poor achievement for the Geo-environmental properties on the long run
26 - Effect of the used material on environment on the long run

4. AHP Model Framework

The (AHP) was developed by (Saaty 1980) to solve decision making problems prioritization of decision alternatives and widely used in decision making systems. AHP has been implemented in construction projects decision making and risk assessment to solve many problems (Dikmen & Birgonul 2006; Zayed *et al*. 2008; Zeng *et al*. 2007). The AHP models decision making framework that assumes a unidirectional hierarchical relationship among decision levels (Presley 2006). The hierarchical approach allows AHP to investigate the interrelationships amongst sustainability criteria. This is important as the various aspects and criteria pertaining to sustainable development are often linked together (Singh *et al*. 2007).

In this work, an AHP model is introduced, as it is offered a logical and representative way of structuring the decision problem and deriving priorities. The main purpose of this model is giving support for choosing C or GCM as a stabilizer material in embankments construction projects in Japan. After arranging the problem in hierarchical terms, a calculation for relative importance of each identified criterion, using a pairwise comparison technique as suggested by (Saaty 1986), is done and applied for the four identified criteria. For example, many questions can be asked to the decision makers such as "How Important is (criterion 1) when it is compared to (criterion 2)". The second level of questions combined the four criteria interchangeably and the choice of using C or GCM. An example of a question in this level like "How important is (criterion 1) when it is compared to the use of C or the use of GCM". The model consists of one matrix in the first level and 4 matrices in the second level.

The comparisons are done by utilizing the preference scale introduced by (Saaty 1980). The pairwise comparisons from each branch at each level of the hierarchy are entered into a matrix and used to determine a vector of priority weights. The decision maker should choose a defined number from 1 to 9 to perform pairwise comparisons on the elements. The nine-point scale can be defined as: 1 refers to "equal importance", 3 refers to "somewhat more important", 5 refers to "much more important", 7 refers to "very much more important", and 9 refers to "absolutely more important". The consistency ratio (CR) is calculated as a measure of cognitive effort in the decision which is calculated as follows:

CR = CI\RI

Where: (CI) is consistency index and (RI) is relative importance or eigenvector. They are calculated according to the procedure presented in previous work of (Saaty 1980).

5. Case Study Description and Model Application

The investigated case study in this research is the construction of two embankments namely A and B located in Ota city, Gunma Prefecture, Japan. The location of the investigated project is shown in Figure 1. This project is constructed to protect a new industrial area located in Ota city against flood and rainfall hazards. The height of embankments is 15 m while the projection area for embankments body is (79×112 m). The served area by this project is 410000 m^2. The required compressive strength for this project is 130 kPa based on design criteria while the required strength in site based on the result of cone index test should be more than 260 kPa because the used factor of safety in this project is equal two. The acceptable compacted thickness for each layer of embankments after the completion of compaction process is 25 cm. The designed mixing percentage of recycled gypsum and cement as a solidification agent, used in this project was 4 and 2.5 %, respectively based on dry soil mass. Recycled gypsum used in this project was brought from local waste recycling company at Ashikaga city in Gunma Prefecture. The type of solidification agent used in this project was blast furnace slag type-B and this cement type is produced mainly from by-product of Portland cement. It was brought from local cement company in Tokyo. The owner of this project is Ota city hall while the contactor is one of the biggest national construction companies in Japan. Primary investigations, design requirements and construction process were done by the contractor while the consultation was done by laboratory of geotechnical engineering at Gunma University. Besides, there was another specialist for the application of recycled gypsum in earthwork projects from University of Miyazaki shared in the consultation decision.

The second brainstorming session is conducted with major construction project stakeholders in this project to get the data which feed the model. This step was done by a question and answer session to make sure that everyone fully understood each response. All attendees were informed by the objective of the session for enhancing its efficiency. Several comparison matrices are introduced. The goal of the analysis is to support the choice for one of the available two stabilizer materials to be used in the investigated project. The four identified criteria are affected by 26 factors which are explained for the attendees and they have asked which of them have the same effect on the two stabilizer materials and why the other factors have different effects. Table 2 shows the resulted comparison matrix for the four criteria.

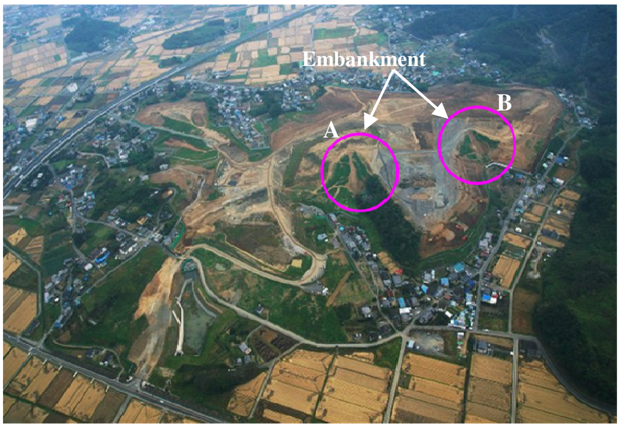

Figure 1. Location of the investigated project

Table 2. The comparison matrix for the four criteria

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Criterion 1	1.000	0.333	0.333	0.333
Criterion 2	3.000	1.000	1.000	3.000
Criterion 3	3.000	1.000	1.000	3.000
Criterion 4	3.000	0.333	0.333	1.000

The consistency ratio was found to be 7.12 %, which is less than 10% and then the matrix is considered consistent. For the second level, 4 matrices are filled as explained before. The collected data conclude that the GCM is much more important for Criterion 1, the cement is somewhat more important for criteria 2 and 3, while the GCM is somewhat more important for criterion 4. The Final decision is that the model supports to use the GCM by a percent of 60.60 % versus 39.40 % to use C which means that using GCM is preferable by 50%, approximately.

Figure (2) shows the number of factors which (have the same effect) and factors (have different effect) on the two stabilizer materials due to the brainstorming discussion. More discussion for dealings of the stabilizer materials with factors will be explained in next section.

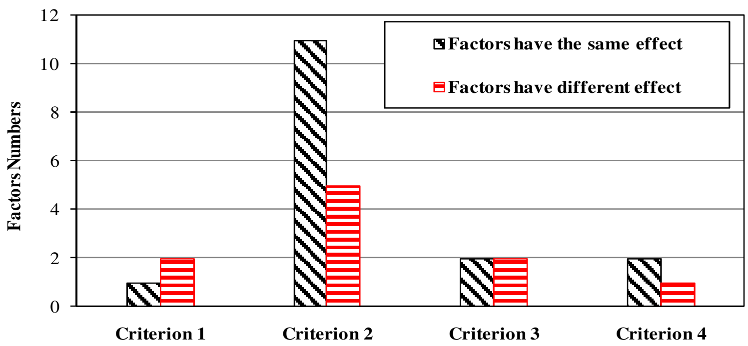

Figure 2. Factors pattern for the investigated criteria.

6. Discussion and Analysis

As mentioned previously, there are main four identified criteria, influencing the decision making for using C or recycled GCM as a stabilizer material in the investigated case of embankments construction project. First criterion is saving in cost due to using GCM instead of C. In fact the price of cement is higher than recycled gypsum price. Based on the available data in construction market in Japan during the execution time, the cost of the stabilization for one cubic meter of the tested soil in this project using C is higher than using GCM by about 31%. In addition, introducing of recycled gypsum as a stabilizer material is associated with saving land price required for gypsum wastes disposing in landfill sites. It is well-known that the price of land in Japan is very expensive due to the limited area there. There is no difference in routine works such as site investigation, preparation of boring reports, design, excavation, handling materials, mixing, compaction, and in-site tests either using C or GCM.

The second criterion highlights the factors associated with the execution stage (project scope achievement). There is no much difference between execution activities used in case of using C or GCM as a stabilizer material. In both cases, the procedures of construction approximately are the same as presented in the execution steps previously. Figure 3 shows some in-site activities during the execution process. In brief, the steps of construction in the investigated project are including collection a volume of soil by excavation from the site, transporting the soil to mixing area, mixing soil with stabilizer, transporting the soil to its original place, compacting using specified rolling machine, and checking the strength by testing the compacted layer in-site. So, it can be concluded that, the procedures of construction almost are the same. While in the case of using GCM as a stabilizer, a simple pump is used for spreading water during the mixing stage, especially in bad weathering conditions such as windy days. The main target of spreading water in this stage is to overcome the developed dust during mixing process since gypsum has small density compared to cement. This activity is essential in site to avoid any negative effect on workers' health and meet the standards of safety in construction according to Japanese regulations.

The administrative approval may need more efforts when using gypsum compared to using cement. This issue is essential to use any type of waste or recycled materials in geotechnical applications according to Japanese regulations to avoid any environmental problems. Generally, this issue is considered one of the drawbacks of using recycled gypsum in ground improvement in Japan. While, it may not be applied in case of C since cement is considered approved material in the construction of ground improvement projects in Japan. On the other hand, the use of recycled gypsum has a positive effect compared to cement when the investigated soil contains high water content. This is due to the potential of gypsum for absorbing water from the moist soil is higher compared to cement. This property helps in the reduction of construction time and cost.

The third criterion deals with one of the important issues especially when waste or recycled materials used as alternative materials in construction industry, which is durability. Durability is defined as the resistance of materials against weathering conditions. There are several tests used to evaluate the durability of materials used in construction such as freezing-thawing, wetting-drying, and soaking tests. As mentioned in the section of introduction, the solubility of gypsum is considered one of the drawbacks for using recycled gypsum as a stabilizer in ground improvement projects. Previous studies dealt with issue and provided acceptable and reasonable results for the improvement of the durability of soil stabilized with recycled gypsum by the incorporation of solidification agent in soil-gypsum mixture such as cement or lime. In this project, furnace cement type-B was used as a solidification agent to improve the durability of the project as presented in previous work (Ahmed *et al*. 2011a).

There is no doubt that the durability of soil stabilized with C is higher if compared to that stabilized with GCM. In this project, the durability against soaking condition is investigated and reasonable results were obtained as presented in previous work (Ahmed *et al*. 2011c). Ultimately, it can be said that the selected percentage of mixing for GCM used in this project achieved acceptable durability compared to the durability of identical sample stabilized with C based on the results presented by (Kamei *et al*. 2013a; Ahmed *et al*. 2011a). To avoid any problems related to durability in future, the process of mixing should be done perfectly to meet reasonable durability. Consequently, more attentions should be given for the process of mixing in this project to avoid any negative effects on the future durability.

Figure 3. Construction steps for the investigated embankment project

The fourth criterion deals with the geo-environmental impacts when C or GCM incorporated in this project as a stabilizer material. The use of gypsum or cement as a stabilizer in ground improvement projects has a slightly effect on the environment and this effect is varying from project to another. There are many factors control the geo-environmental properties of earthwork projects when gypsum or cement is introduced as a stabilizer. The main two parameters control the geo-environmental impacts is type and amount of the used stabilizer. As mentioned early, the use of gypsum without addition of solidification agent has a negative effect on the environment due to the emission of hydrogen sulfide gas and the release of fluorine more than the standards (Kamei & Horai 2008). Previous studies proved that, adding of solidification agent such as cement or lime with specific percentage has a significant effect on the improvement of geo-environmental properties (Ahmed *et al*. 2011a).

In order to achieve acceptable geo-environmental properties, furnace cement was added to the used recycled gypsum with specified content to meet the standards of environment. While the use of C as a stabilizer material in this project has also a negative effect on the increase of (pH) and the release of hexalavant chromium more than the standards. Generally, it can be concluded that the incorporation of GCM as a stabilizer material in this project is friendly with the environment compared to the use of C based on the results presented in previous work, which is related to the execution of this project (Ahmed *et al*. 2011a). Besides, using recycled gypsum produced from gypsum wastes as a stabilizer in this project supports the environment. This can be done by reducing the quantity of gypsum wastes disposed in landfill sites, eliminate the cost of their disposing in landfill sites and reduce the cost of project.

7. Conclusions

As mechanical ground function for materials selection based on wastes for ground improvement projects is important, also the consideration of decision-making in the evaluation of using wastes as alternatives is essential. Therefore, a multi criteria decision-making model to support the decision makers who deal with the application of wastes in ground improvement projects for a case study in Japan is proposed. This is done to evaluate the incorporation of recycled gypsum produced from gypsum wastes as an alternative stabilizer material in embankments construction project. The proposed model embraced the broader sense of cost, scope achievement, durability and geo-environmental impacts for ground improvement projects. The model used the AHP for comparing the two suggested materials, which is C or GCM, used in the investigated construction project as a stabilizer material. Based on the results obtained in this study, the specific conclusions can be drawn as follows:

1. The model results proved that the use of GCM as a stabilizer in this project is better compared to the use of C. The Final decision was that the model supported the use of GCM by a percentage of 60.60 versus a percentage of 39.40 % for using C.
2. The execution activities in both cases is almost the same and then the saving in cost in this project is mainly related to material price and saving in the price for the disposing of gypsum wastes in landfill sites.
3. Both materials used as a stabilizer in this project are in agreement for the effect of sixteen factors while there are significant differences for their dealing with other ten factors that control the decision making.
4. The results obtained in this study supports the application of recycled gypsum as an alternative stabilizer material in ground improvement projects which helps in the protection of environment by introducing waste materials as alternative material in construction industry based on decision making in advance.
5. The developed model used in this study is suitable for other case studies and it can be adopted for that.

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