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Full Length Research Paper

The compressive strength and planting properties of cemented sand and gravel material compacted by the Hilti vibrating method

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This study was performed to evaluate the compressive strength of cemented sand and gravel (CSG) material with the Hilti vibrating compaction method and the effects of variables such as curing age and to investigate the planting properties of these CSG blocks when seeded with herbaceous plants and cool-season grasses. Four types of CSG mix designs and cement contents were evaluated by a compressive strength test, and two types of CSG mix designs were tested as planting blocks. To analyze the growth properties of plants in the CSG blocks, the initial germination ratio and period, visual cover and plant height were measured at 4 to 12 weeks after seeding. The results showed that the compressive strength of the CSG material increased as the cement content and curing age was increased. The initial germination started within 5 to 8 days after seeding regardless of the kind of plant or type of CSG block, and the germination ratios were in the range of 55 to 60%. The visual estimation of the cover of the different kinds of plants appeared over eight points for all blocks at eight weeks after planting.

Key words: Hilti vibrating, cemented sand and gravel, planting, germination, cover view.

INTRODUCTION

There are two ways to improve the cohesion and strength of soil: Using cement-series soil in the soil/cement mixture or using soil cement. Soil is often used to pave bike-exclusive roads, parking lots and public plazas, as well as in other fields, such as protecting slopes and improving weak foundations. Soil, which is regarded as an economic and environmental-friendly construction material compared with concrete, is often mixed with cement or cement-series firming agents to improve strength by increasing its cohesion. Many studies have been conducted on this topic in Korea and elsewhere.

Kim et al. (2003) investigated the correlation between soil- cement mix proportion, by soil grain-size distribution and curing period on the unconfined compression strength and flexural tensile strength when a special firming agent was used as a binder. Kim et al. (2004) conducted X -ray diffraction analysis and a dynamic cyclic-loading creep test to evaluate the unconfined compression strength and time-dependent behavior when a firming agent is added to weathered granite soil. In addition, Sabry et al. (2001) assessed the durability, defined as the long-term unconfined compression strength, and studied how a soil cement mixture consisting of 3 types of soil and sulfate-resistant cement would freeze and thaw. Venkatarama et al. (2007) assessed the strength, absorptance and durability of soil-cement blocks to analyze the effect of soil grain size on these parameters.

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Table 1. Mix designs of CSG materials with cement contents (Unit: kg/m^3).

Type	Cement	Aggregate	Water	W/C
CSG-0	0	2,204	187	-
CSG-80	80	2,126	188	235
CSG-100	100	2,114	188	188
CSG-120	120	2,100	189	157

Cemented sand and gravel (CSG) materials, which are primarily used in Korea and Japan, are created by mixing water and cement with excavated gravel. CSG materials are mostly used in dam construction, where a dam is constructed building consecutive embankments made of CSG material and compacted with a vibrating roller (Kim et al., 2005; Bae, 2006).

There are no clear criteria for testing the methods used in compaction of CSG materials; existing mechanical soil-compaction methods are used as they are. Other compaction methods may be done according the standard compaction (ASTM D 698) and revised compaction (ASTM D 1557) methods used in the U. S. roller compacted concrete (RCC) method. The lack of a standard method is a result of the scarcity of studies looking at the factors that influence the mechanical characteristics of CSG materials (Kim et al., 2005).

As the demand for environmentally-friendly construction increases, there is more research on eco-friendly methods of construction for revetments and inclined planes, and environment friendly methods of construction in places likely to provide habitats for plants and animals (Sung et al., 2002, 2003).

Therefore, to analyze the compressive strength of compacted CSG material and vegetation characteristics, this study attempted to evaluate the germination rate, degree of cover and growth of plants on a CSG vegetation block on which cool-season grass and Lespedeza cuneata, a traditional native plant were grown. We also investigated how the unit weight of cement in CSG material and the degree of aging affects the compressive strength.

MATERIALS AND METHODS

Materials used

The maximum size of the aggregate used in the CSG method was less than 150 or 80 mm, and the on-site grain size was used as is, without being controlled. However, in the laboratory mix design, large-sized grains could not be used due to restrictions in the experimental equipment, thus, an aggregate with maximum thickness of less than 40 mm was used.

This study used excavated material, obtained during bed excavation, divided into the following size groups, and separated by a sorter: 20 to 40, 10 to 20, 4.76 to 10 and < 4.76 mm. Ordinary portland cement with a specific gravity of 3.15, made by H Company in Korea, was used in this study.

Mix design and production

Mix

Currently, there are no clear criteria for the mix design in the CSG method, but two mix design methods are generally used: The soil mechanical method, which estimates the unit weight of the material with a compaction method; and the concrete mix design method, which provides the optimal mix design according to the water/cement ratio and the unit weight of the aggregate.

In this study, the optimal mix was determined by a pre-test that calculates the design criteria strength after compaction at the optimal moisture ratio. This is done by measuring the optimal moisture ratio and the maximum dry density according to the unit weight of the cement after the compaction tests. To compare and assess the characteristics of the unconfined compression strength of CSG materials after Hilti vibration compaction, 4 different mixes were prepared, referred to, as CSG-80, CSG-100 and CSG-120, where the numerical value denotes the unit weight of the cement that was used (80, 100 and 120 kg/m^3). Also, the mix with no cement, designated CSG-0, was used to provide a comparison with the vegetation characteristics of a non-cement mix. Table 1 shows the mix designs of the CSG materials according to the unit weight of the cement. Figure 1 shows the distribution of the grain size of the excavated material.

Compaction

There are no clear criteria suggested for compaction methods of CSG materials thus, the existing soil mechanical compaction methods were adopted as they are. In Korea, studies on CSG materials primarily use compaction methods with Revision E compaction. Therefore, this study performed compaction tests based on the Hilti vibrating method (ASTM C 1435), suggested by the U. S. RCC, to assess how the strength characteristics of CSG material changes with the compaction method used.

Production of test piece specimen

Each test specimen was produced by inserting the CSG material into a concrete mold (15 cm diameter, 30 cm height) that was divided into three sections. Each section was then compacted by the Hilti vibrating compaction machine for one minute. For the compressive strength tests, 12 test specimens from each mix were produced, and the procedure was repeated 3 times. To verify the strength characteristics after aging, the test specimens were cured for 3, 7, 28 and 91 days. Figure 2 shows the Hilti vibrating

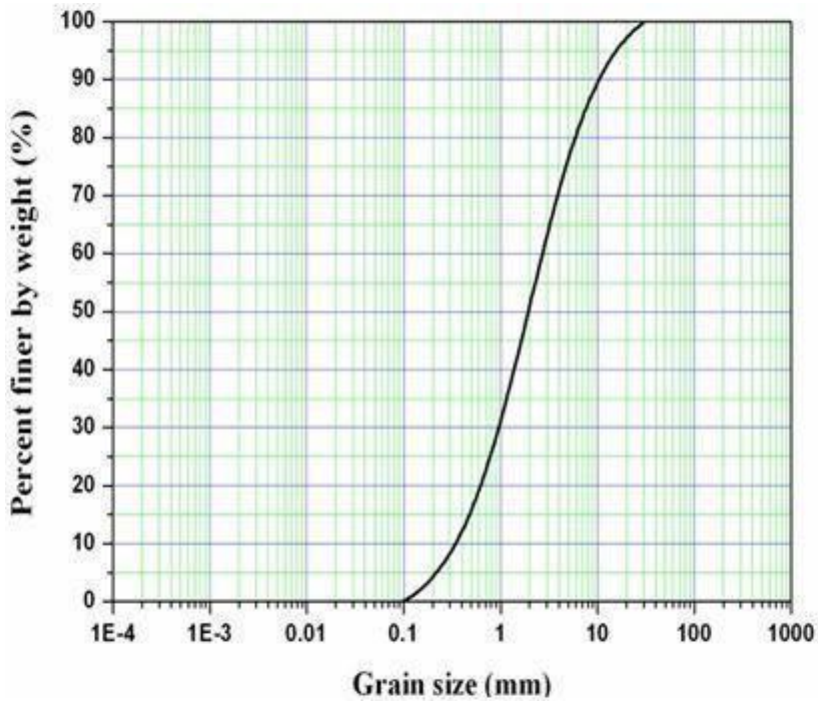

Figure 1. Distribution curve of grain size.

Figure 2. Hilti vibrating machine.

compaction machine and a block for planting.

Production of the CSG blocks

A 20 × 20 × 5 cm vegetation block was created to assess the germination rate, degree of cover and growth rate of the plants. Hilti vibrating compaction was conducted to assess the compressive strength of each test specimen. Figure 3 shows a test specimen used with Hilti vibrating compaction to test the compressive strength.

Application to vegetation

For the vegetation, grass and native plants were used because they are widely used in slope construction due to their high covering-density and superior and fast growth rate. In particular, the Tall fescue and perennial ryegrass were selected as cool-season

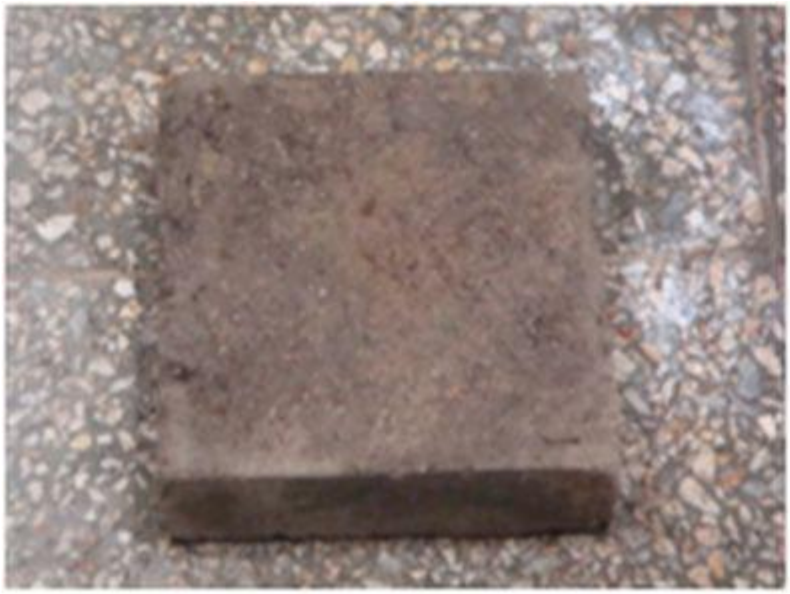

Figure 3. Block for planting.

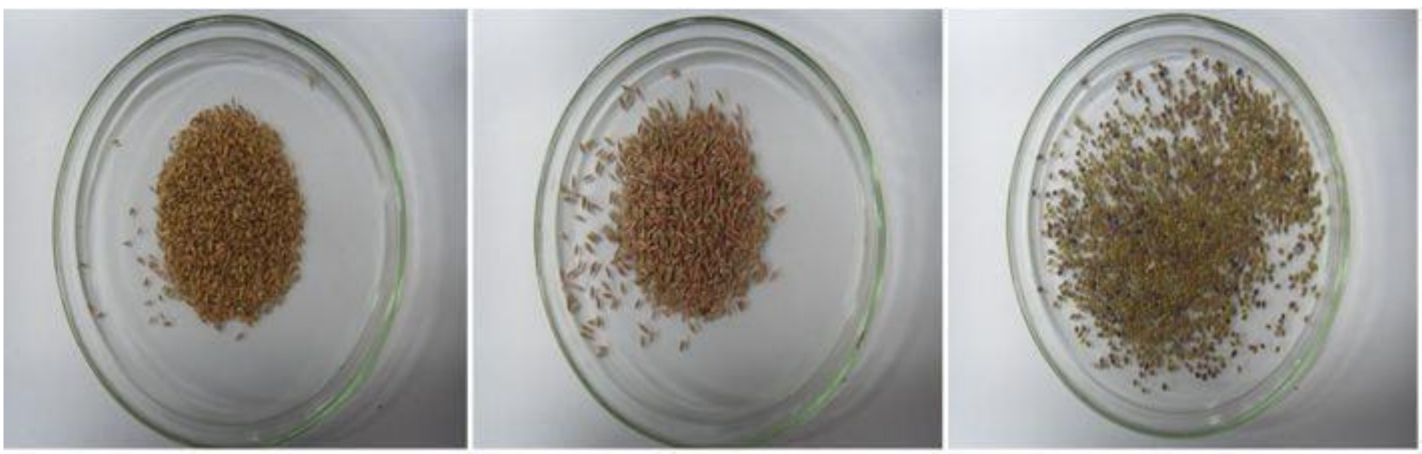

Figure 4. Kinds of seeds that were planted.

grasses due to their excellent resistance to cold and heat, which means that the grasses adjust well to a wide range of soil conditions. Lespedeza cuneata was also selected as a warm-season native plant, which is a perennial ryegrass that grows in sandy soil, for example, at the foot of a mountain or riverside. The plant seeds were provided in 3 mixtures of single-breed seeds and 1 mixture of 3 mixed-breed seeds. Figure 4 shows the kinds of seeds planted for vegetation.

To assess the degree of cover of each plant according to the germination rate and growth increment of the plants, the amount of seeding used was 1.2 g for the tall fescue and perennial ryegrass and 0.9 g for the *L. cuneata*. The seeds were planted in culture soil on the CSG block, and sufficient moisture was provided to promote the germination and growth of the seeds. The plants were grown for a certain period of time in a green-house at temperatures between 25 and 32°C.

Test methods

Compressive strength test

The compressive strength test was performed on the basis of the KS F 2405 method, which tests the compressive strength of concrete by sustaining the load at a rate of 1 mm/min with a universal testing machine from the Instron Company.

Test for vegetation characteristics

To analyze the growth characteristics of plants on the CSG block, the germination rate, degree of cover and growth rate of the plants were measured for 12 weeks after planting. The germination rate and degree of cover were observed with the naked eye. The degree

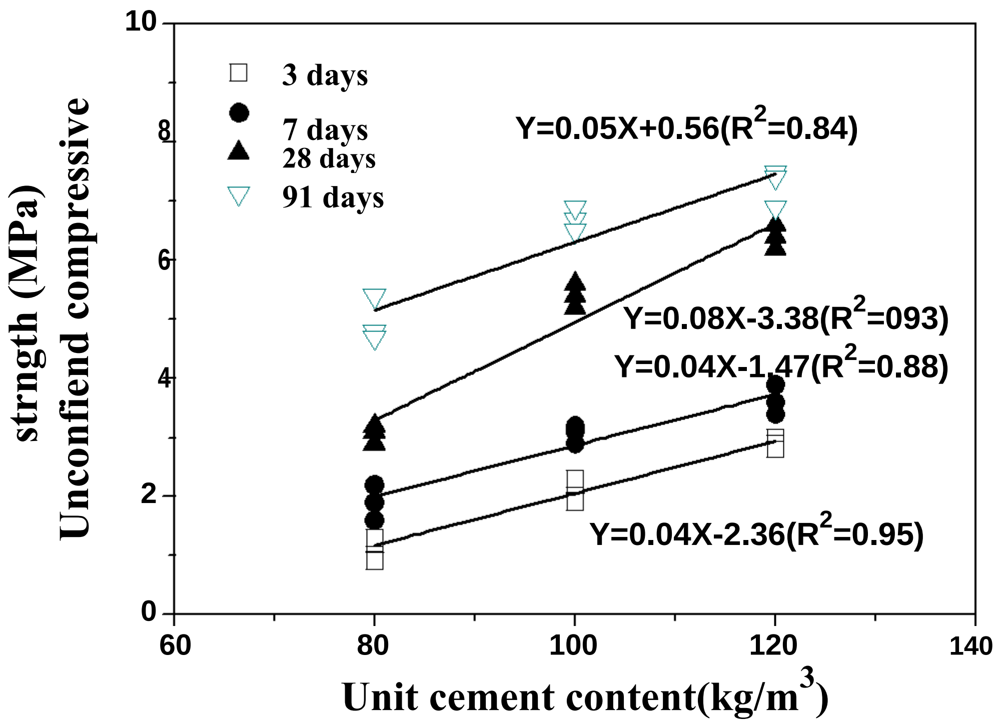

Figure 5. Compressive strength of the compacted CSG material.

of cover was evaluated on a 9-point scale using a visual rating system (Kim et al., 2003), where 1 represented the least amount of coverage, and 9 represented the maximum amount of coverage. Also, the growth increment was estimated with a qualitative assessment by directly measuring the height of a plant from the ground.

RESULTS AND CONSIDERATIONS

Characteristics of CSG material

Compaction

From the compaction tests, the optimal moisture rate of the CSG-80 mix was determined to be approximately 8.5%, and the optimal moisture rates of the CSG-100 mix and CSG-120 mix were approximately 8.4 and 8.5%, respectively, showing that the optimal moisture rate hardly changed with different unit weights of cement. In contrast, the maximum dry density of CSG-80 was determined to be 2.07 g/cm^3 at its optimal moisture rate, and the maximum dry densities of CSG-100 and CSG-120 were 2.1 and 2.12 g/cm^3, respectively, showing that as the unit weight of cement increases, the maximum dry density increases as well to a small degree. This result is similar to the results of Kim's research (2006), which showed that while there was no change in the optimal moisture rate according to unit weight of cement in compaction tests of CSG material, the maximum dry density increased as the unit weight of cement increased.

Compressive strength

Unit weight of cement and compressive strength: Figure 5 shows the compressive strengths of each curing age according to the unit weight of cement of the compacted CSG material. For the CSG-80 mixture, the compressive strengths of the 3- , 7- , 28- and 91-day specimens were 1.1, 1.9, 3.1 and 4.9 MPa, respectively, which shows that the compressive strength greatly increased as the duration of ageing increased.

For the CSG-100 and CSG-120 mixtures, the compressive strength of the 3-, 7-d, 28- and 91-day specimens were 2.1, 3.1, 5.4 and 6.7 MPa and 2.9, 3.6, 6.4 and 7.2 MPa, respectively, which shows that as the unit weight of cement increases, the compressive strength increases, regardless of age.

Using the Hilti compaction method, compressive strength according to unit weight of cement exhibited similar trends to the research results of Yeon et al. (2010), where Revision E compaction was used; thus, no difference in strength was observed by using the two compaction methods. In another study, Bae (2006) studied the compressive strength of CSG material and discovered that because the strength increased at a

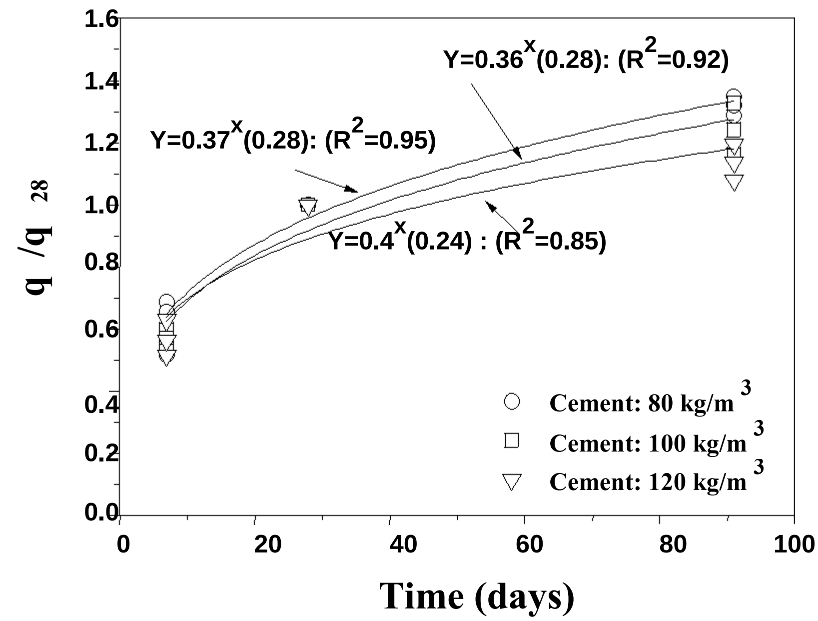

Figure 6. Strength ratio of the CSG material.

higher rate when the unit weight of cement increased from 80 to 100 kg/m^3 compare with when the unit weight of cement increased form 60 to 80 kg/m^3, the strength of CSG material is influenced significantly by cement when the unit weight of cement exceeds 80 kg/m^3.

In this study as well, the strength increase rate was higher when the unit weight of cement increased from 80 to 100 kg/m^3 than when it increased from 100 to 120 kg/m^3. Therefore, the compressive strength does not linearly increase with the amount of cement once the unit weight of cement reaches a certain value. Thus, it will be necessary to determine the optimal mixture that satisfies both the design criteria strength and economic feasibility when deciding the unit weight of cement to use. In this study, when 100 kg/m^3 cement was mixed, the compressive strength of the 28-day specimen was greater than 6 MPa, which indicated that its effect when used in cement combinations was higher than in the other mixtures.

Age and compressive strength: Figure 6 shows the strength ratio between each aged specimen and the 28-day specmen for different unit weights of cement. The compressive strengths of the 3-day and the 7- day specimen compared with the compressive strength of the 28-day specimen were 37 and 62%, respectively, and the compressive strength of the 91-day specimen compared with that of the 28-day specimen was 132%, which indicates that the compressive strength increases as the degree of aging increases.

These results show that the strength increases to some degree when the density increases due t o compaction when cement is not mixed with soil. However, in cement soil mixtures, the cohesion of the soil grains increases due to hydration from the cement hardening, which also seems to strengthen the cement. In addition, the strength ratio for each aged specimen compared with the 28-day specimen for the CSG-100 mixture exhibited almost identical trends as that in the CSG-80 mixture. Furthermore, the strength ratio for each aged specimen compared with the 28-day specimen for the CSG-120 mixture also exhibited almost identical trends as those in the CSG-80 mixture and the early-aged CSG-100 mixture. However, the strength ratio of the 91-day specimen was relatively low, which indicates that there were a few differences, depending on the amount of mixed cement. For the mixed soil case, when a cement combination of 3% was used, there was hardly a strength increase after 7-days of aging, but when a cement combination greater than 6% was used, there was a constant strength increase as aging increased, which is similar to the results of Song et al. (2002).

Growth characteristics in the vegetation block of CSG materials

Germination rate

Figures 7 and 8 show the germination appearances of each vegetation type in the CSG blocks of CSG-0 and CSG-100, 2 weeks after planting. With the Lespedeza cuneata, a traditional native plant, early germination began approximately 5 days after planting and showed

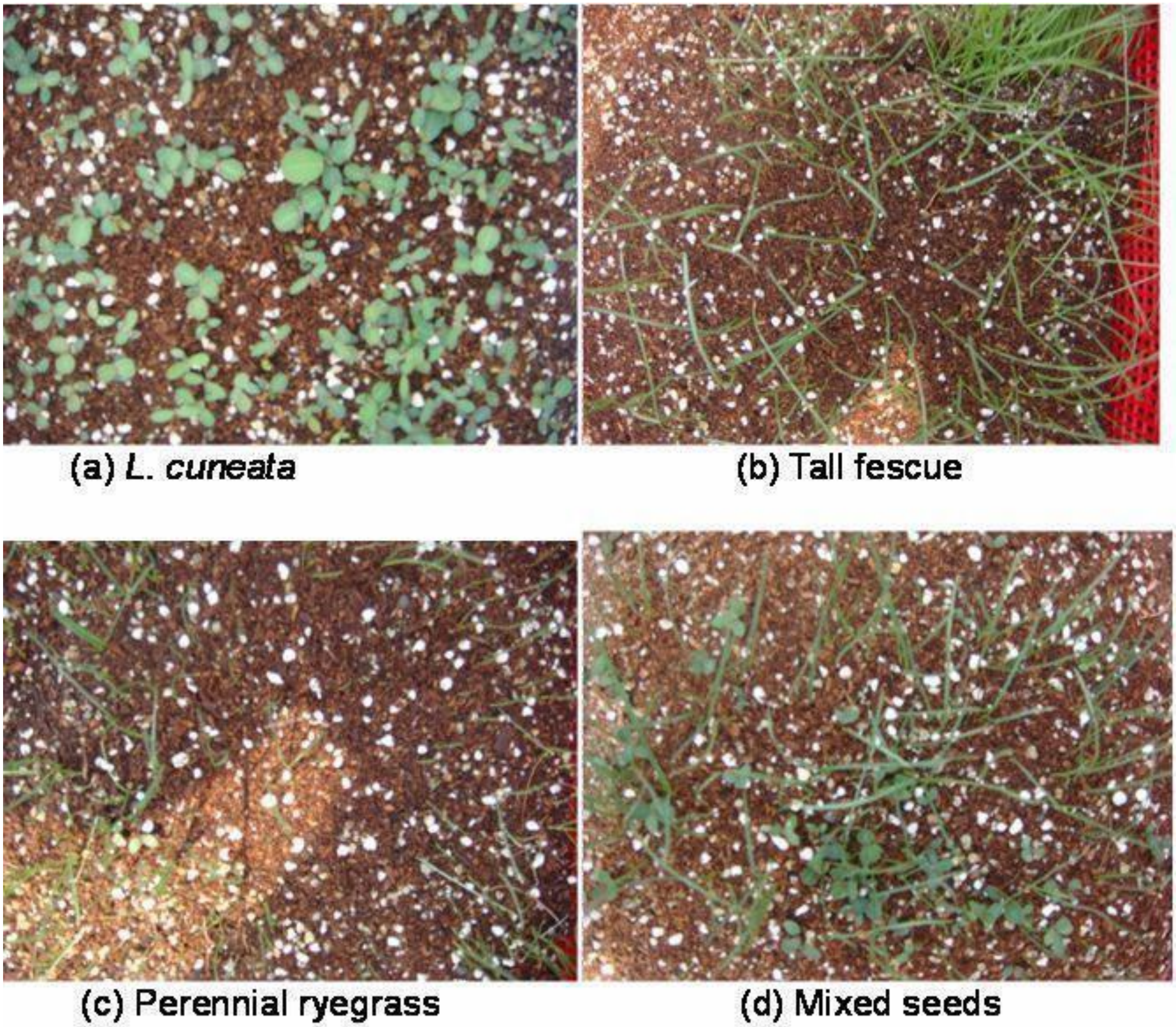

Figure 7. Germination view of each type of plant (CSG-0).

approximately 60% of the early germination rate, regardless of the CSG block.

For the of tall fescue and perennial ryegrass, early germination began 6 to 8 days after planting regardless of the CSG block, and their early germination rates were both approximately 55%. Their early germination rates and germination timings were similar because the germination environment was improved by spreading culture soil on the block before seeding. In contrast, the germination rate for tall fescue and the perennial ryegrass in ordinary soil can reach up to 70% between 6 and 9 days and between 5 and 6 days after planting, respectively, depending on the breeds, germination conditions and growth environments, similar to results by Kim et al. (2003).

From these findings, the germination timings were essentially the same, but the early germination rates were relatively low. It seemed that because the temperature of the green house was greater than 30°C at the time of planting, their germinations were slightly delayed. The early germinations and germination rates of the plants in the block where both the cool-season grass and *L. cuneata* were planted were essentially the same as the plants in the blocks where single-seeds were planted.

As shown in Figures 7 and 8, 2 weeks after planting, the germination rates of the plants in the CSG blocks were greater than 80%, regardless of the CSG mixture

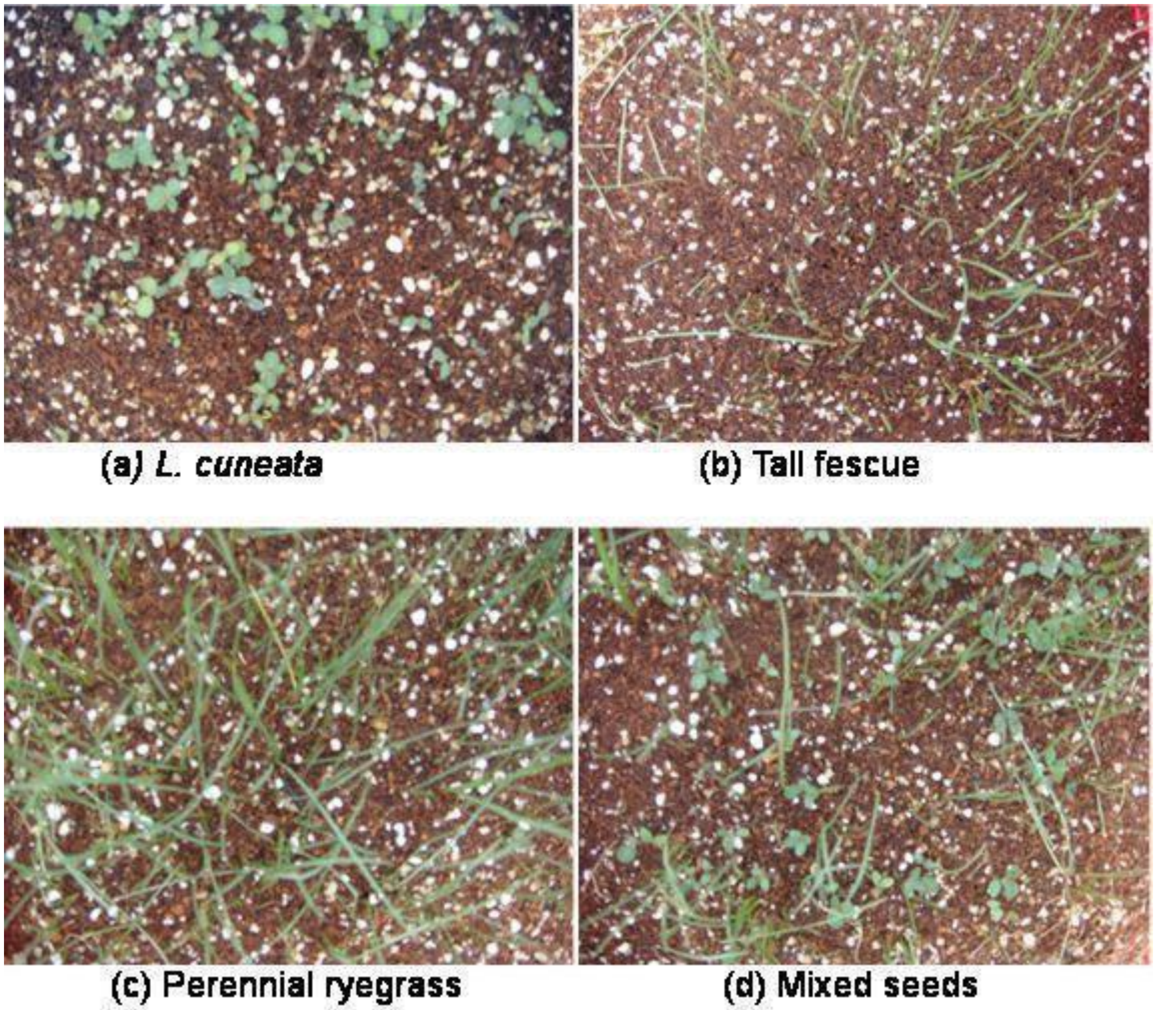

Figure 8. Germination view of each type of plant (CSG-100)

and the plant breeds. Therefore, considering the high germination rates of the plants in the CSG-100 mixture, it is expected that developing environmentally-friendly methods of construction will be possible because of the strength increase of mixed soil combined with cement and the growth and development of plants. Also, when tall fescue, perennial ryegrass and *L. cuneata* are planted, their early greening, fast early germination and high germination rates will be highly advantageous.

Degree of coverage

The amount of vegetation covering the CSG block was investigated using a visual rating system 8 weeks after planting and evaluated on a 9-point scale, where 1 represented the smallest degree of coverage, and 9 represented the highest degree of coverage (Kim et al., 2003).

Figures 9 and 10 show the degree of coverage for the different CSG mixtures and the vegetation breed 8 weeks after planting. As shown in Figures 9a and 10a, *L. cuneata* was found to have the most desirable score (9 points) in the CSG -0 mixture. Because it may be difficult for *L. cuneata* to fix or expand its roots due to the strength increase of the CSG block and its straight-root properties, the proper seeding timing and environment will be required for better growth, especially in the early time of seeding (Yeon et al., 2010).

As shown in Figures 9b, c, 10b and c, both the tall fescue and the perennial ryegrass exhibited a high degree of cover (greater than 8 points), regardless of the CSG mixture, especially in the CSG-100 mixture. Perennial ryegrass exhibited the most desirable degree of cover with 9 points. The reason why cool-season grass displays a superior degree of cover 8 weeks after seeding, regardless of the CSG mixture, is that the foreign, cool-season grass exhibits a fast, early growth

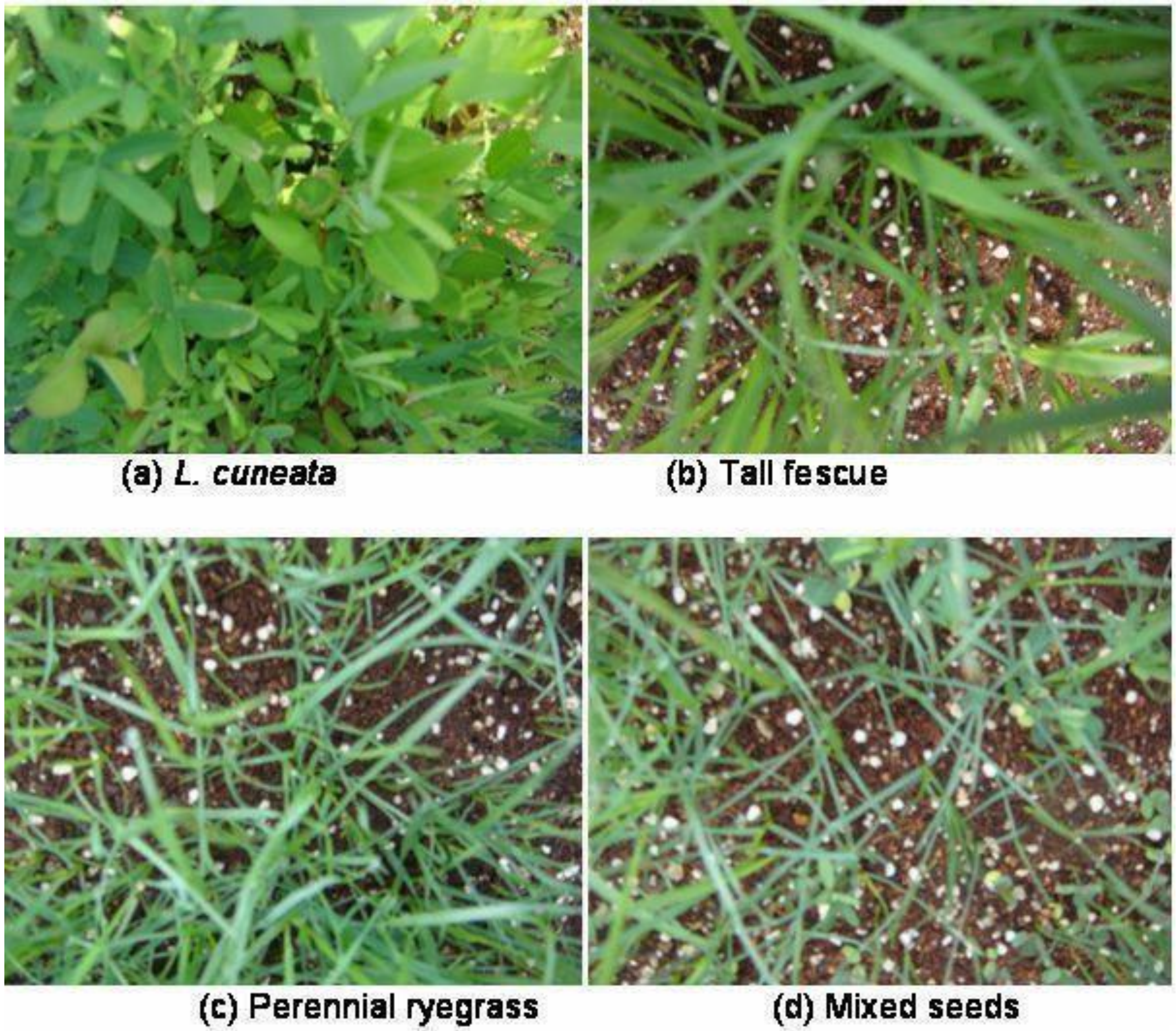

Figure 9. Cover view of each type of plant (CSG-0).

due to its growth habit, which is the bunch-type/B-type. However, as shown in Figures 9b and 10b, because the grass surface displays a clumpy appearance when sprouts grow and in addition with the inherently coarse texture of tall fescue, its degree of uniformity may be lower than that of the perennial ryegrass. Therefore, it is necessary to consider this trait as well (Kim, 2003; Shim et al., 2004).

As shown in Figure 9d and e 10d for the combined seeding case, the grass and *L. cuneata* combination exhibited a degree of cover of 9 points because of their superior growth characteristics, regardless of the CSG mixture. Thus, this combined seeding approach, where traditional native plants and grasses with different growth and leaf characteristics are planted, seems desirable when used in environmental-friendly methods of construction. Moreover, foreign cool-season grass may wither in high temperatures during the summer season in Korea; thus, when the cool-season grass is planted in combination with traditional native plants with relatively superior growth at high temperatures, it would be possible to provide an environmental effect regardless of the season (Lee et al., 2008).

Growth rate

Figures 11 and 12 show the appearances of the plant in the vegetation block for the CSG mixtures and the vegetation breeds 12 weeks after planting. After 8 weeks, the *L. cuneata* in the CSG-0 mixture and CSG-100 mixture had grown over 12 cm on average, as shown in Figures 11a and 12a. After 12 weeks, the *L. cuneata* had grown over 17 cm on average, regardless of the CSG

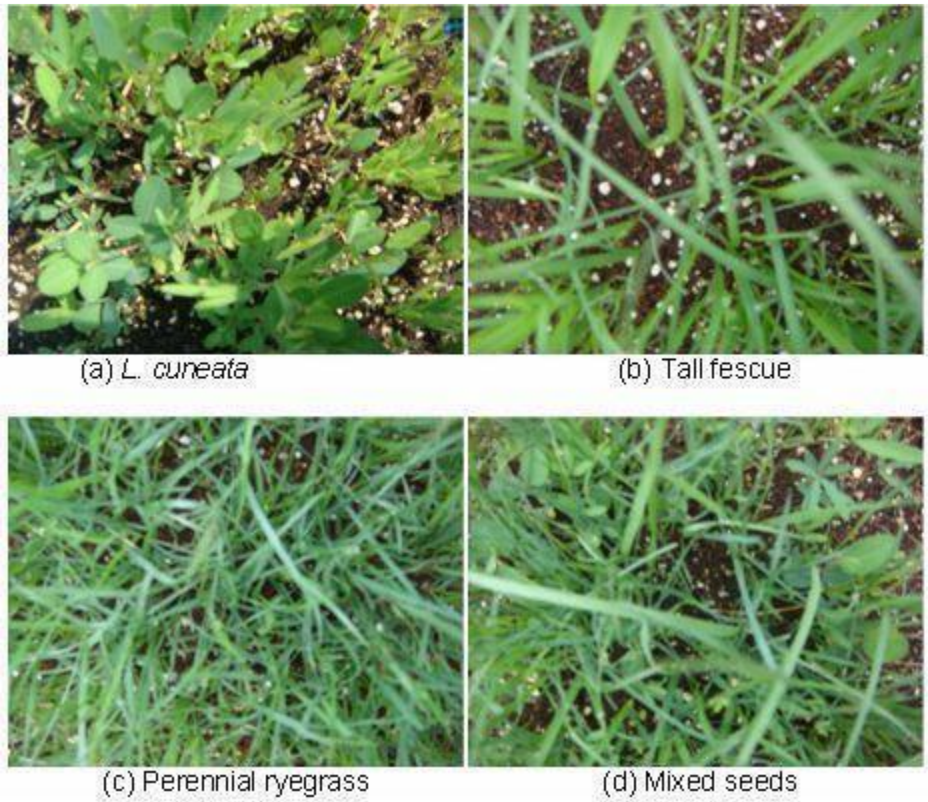

Figure 10. Cover view of each type of plant (CSG-100).

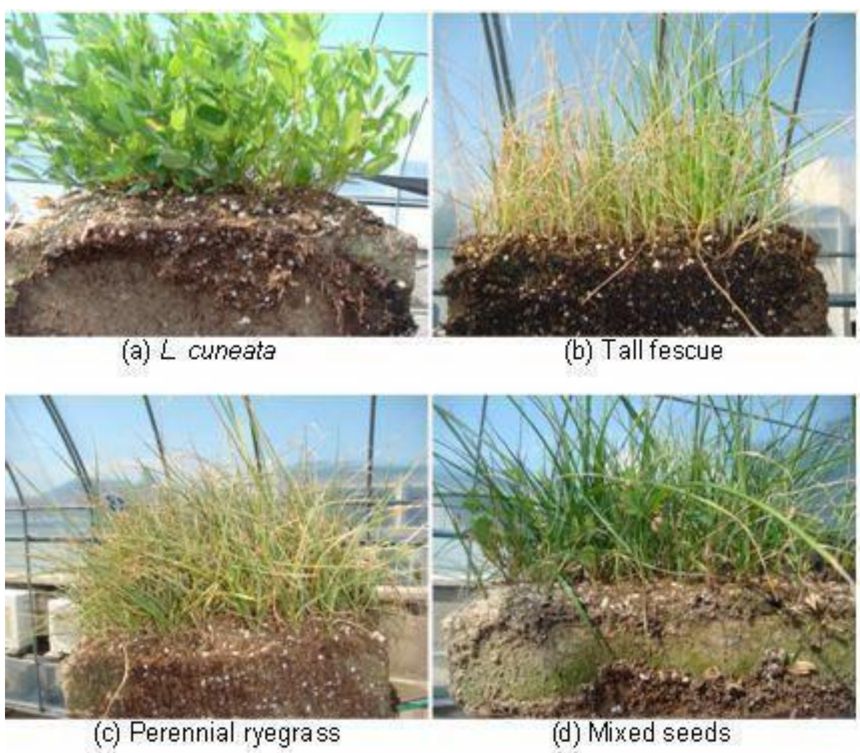

Figure 11. Growth properties of each type of plant (CSG-0).

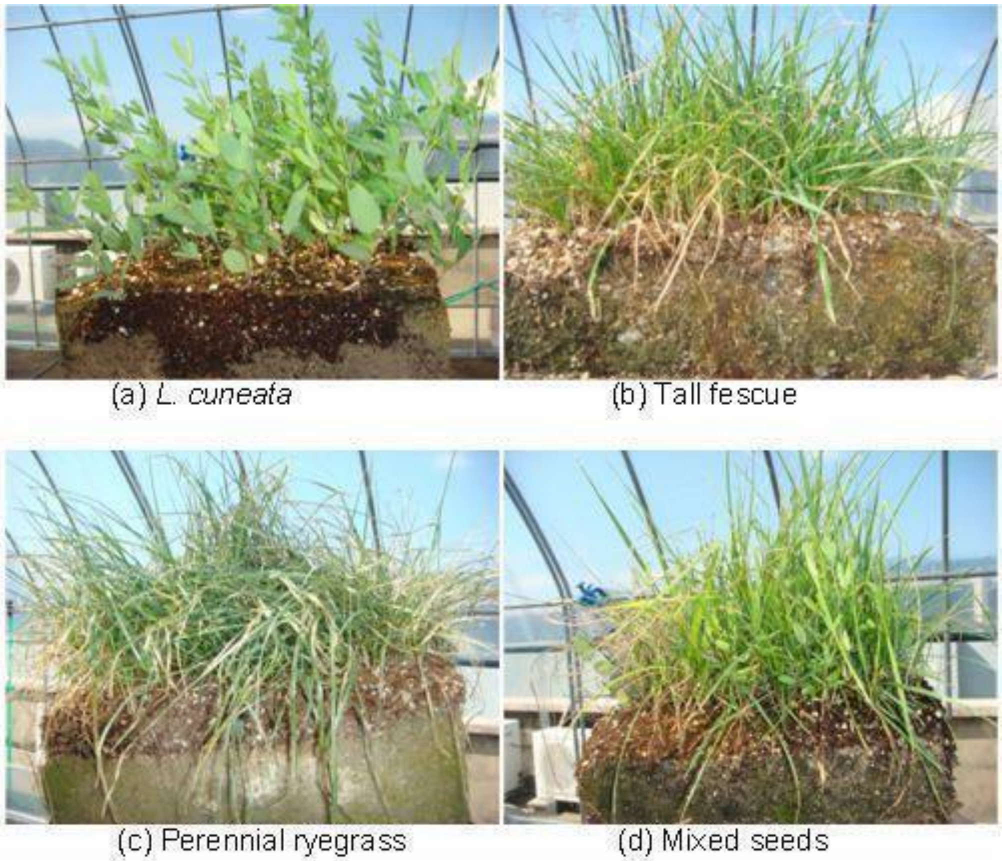

Figure 12. Growth properties of each type of plant (CSG-100).

mixture, which is significant. Because the growth of the leaves and the thickness of the stems of the *L. cuneata* were excellent, in addition to the increased growth rate, the plant would provide a great environmental advantage with its constant growth. Moreover, 8 weeks after planting, its growth rates were 20 and 22 cm for the CSG-0 and CSG-100 mixtures, respectively, which is essentially the same growth rate as that of the tall fescue in the CSG-0 mixture and the CSG-100 mixture. The perennial ryegrass, after 8 weeks, grew 18 cm on average, regardless of the CSG block, exhibiting a rather low growth rate compared with that of the tall fescue.

Furthermore, as shown in Figures 11b, c, 12b and c, 12 weeks after planting, the tall fescue and perennial ryegrass both grew 24 cm on average, which was essentially the same trend as the growth rate 8 weeks after seeding; thus, their growth was slow. It seemed that the cool-season grass, which is relatively vulnerable to high temperatures, would wither or its growth would slow because its environment was sustained at a temperature greater than 30°C 8 weeks after planting. In particular, because the perennial ryegrass not only has a weak tolerance to high temperatures but is also vulnerable to diseases and stress, it seems necessary to consider the effect of its growth environments. The foreign cool-season grass exhibits an excellent germination rate and degree of cover and therefore, it is widely used in environmentally-friendly methods of construction in Korea. However, to minimize the climate effect based on the environmental characteristics in Korea, where temperatures are often greater than 30°C for long periods of time, further studies on planting traditional native plants, such as the *L. cuneata*, which can flourish in the Korean environment, should be performed.

After 8 weeks, the tall fescue exhibited the highest growth rate, though all the plants exhibited a similar trend, with a growth of 17 cm on average in the combined seeding of the CSG-0 mixture and CSG-100 mixture. As shown in Figures 11d and 12 d, the plants were 22 cm on average 12 weeks after planting. In the case of the combined seeding, there were less withered plants compared with the single-seeding with the tall fescue or the perennial ryegrass. As a result, it can be concluded that the combined seeding is more effective for the growth of plants. Furthermore, because the *L. cuneata* and the cool-season grass exhibit different growth characteristics of their leaves, stems and roots and tolerance from each other, they are expected to greatly improve the environmental effect through their mutual supplement process.

Conclusions

The purpose of this study was to verify the germination rate, degree of cover and growth increment of plants in the CSG blocks as well as study how the compressive strength changes with both aging and the unit weight of cement of CSG material which was compacted using the Hilti vibrating method. Thus, from the analysis of the compressive strength of CSG materials and the vegetation characteristics, the following conclusions can be made:

1. The optimal moisture rate for compacted CSG material was determined by Revision E compaction, and the optimal moisture rate was between approximately 8.4 to 8.5%, depending on the unit weight of cement. Thus, the optimal moisture rate did not change significantly as the amount of the cement mixture changed.
2. The compressive strength of the 28-day specimen was 3.1 to 6.4 MPa for cement mixtures between 80 to 120 kg/m^3. Thus, as the unit weight of cement increased, the compressive strength increased as well, and the early strength rate of the 7-day specimen ranged between approximately 56 to 62% compared with the 28-day specimen.
3. For the *L. cuneata*, tall fescue and perennial ryegrass, their early germination began after 5 to 8 days, regardless of the CSG block, and exhibited approximately 55 to 60% of the early germination rate. Also, 2 weeks after planting, their germination rate was greater than 80%, regardless of the CSG mixture and breed.
4. The degree of cover in the CSG block after 8 weeks was greater than 8 points, a desirable degree of cover, regardless of the breed of the plant. Because the *L. cuneata* has a wide distribution of leaves, compared with its early growth rate, it showed a high degree of cover, whereas the cool-season grass exhibited a superior degree of cover due to its high early growth rate.
5. After 12 weeks, the *L. cuneata* exhibited a growth rate greater than 17 cm, regardless of the CSG block. As the growth progressed, the growth of its leaves and stems increased remarkably, and after 8 weeks, the cool-season grass exhibited a high early growth rate, greater than 18 cm. However, after 12 weeks, its growth either decreased or the grass began to wither due to the high temperature of the environment.

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