Applicability of Recycled Gypsum Composite Mortar as Raw Material for Foundation Work of Single-family Houses

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Abstract

This study has confirmed the performance of a recycled gypsum composite mortar (RGCM) foundation, developed for the foundation work of a single-family house using a raw material recycled from waste gypsum boards generated from the construction of new buildings or the demolition of old buildings, equivalent or superior to that of existing foundation work methods. The compressive strength of an RGCM core sample depends on water content and the mixing cement ratio. It is 158 kN/m² for a high water/composite ratio (115%) sample after 28-days of air-drying, which is more than the maximum load of the sleeping foundation (50 kN/m²). The stress of the sleeping foundation can be transferred to the foundation ground. The hardening surface of the RGCM is smooth and there are no problems related to marking and joinability. Even when the excavated surface is rough, the RGCM can be used to fill the gaps resulting from its high fluidity, similarly to the SL material. Thus, the RGCM is integrated with the foundation ground. The RGCM foundation is advantageous from the viewpoints of environmental friendliness (recyclability), and is expected to be used as the foundation footing of houses.

Keywords: flat plate loading test; foundation work; recycled gypsum board; recycled gypsum composite mortar (RGCM)

1. Introduction

The total amount of waste gypsum boards, a construction waste, follows those of concrete mass, asphalt mass, sludge, and wood scraps generated at demolition sites in Japan. A significant increase in the amount of waste gypsum boards is expected in the future (Ministry of the Environment, 2002). Nearly 30 million tons of wallboards are manufactured in North America each year, but a significant proportion of that is wasted (Musick, 1992a). Waste gypsum boards are roughly classified into two groups: those generated at the construction sites of new houses and buildings and those generated at demolition sites. It is estimated that almost 100% of the former is recycled (Musick, 1992b); however, recycling of the latter has been less progressive. The waste gypsum boards generated at demolition sites are piled up at disposal plants. Because they can be a source of hydrogen sulfide depending on the disposal condition, they have been required to be treated at controlled landfill sites since 2006, and they cannot be treated at less-controlled landfill sites even when the paper is removed from them (Ono and Tanaka, 2003; Ono, 2010). The capacity of the controlled landfill sites is very limited and the advancement of the application of recycled waste gypsum boards has become an urgent task (Gypsum Board Association, 2010). The total amount of waste gypsum boards generated at demolition sites is approximately 800,000 ton/year, that of gypsum dihydrate obtained after removing the paper from them 680,000 ton/year, and that of hemihydrate gypsum recycled from gypsum dihydrate is 580,000 ton/year (Ministry of the Environment, 2002). Therefore, it is hoped that a large quantity of waste gypsum boards will be used as recycled material. There are a few examples of the application of waste gypsum boards that are considered effective, such as a material for conditioning roadbeds on soft ground (Kamei et al., 2007) or soil amendment in agriculture (White and burger, 1993). However, the waste gypsum boards generated from houses have not been used as a construction material for new houses and buildings. The authors believe this to be the most effective use of waste gypsum boards from the viewpoint of the management cost of the material and the balance

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between demand and supply.

In this study, the authors focus on the use of waste gypsum boards in the spread foundation on which buildings are directly constructed, which is the first element in the construction of houses (i.e., their use in foundation work), and examined their applicability. Foundation work is carried out on the contact surface between the foundation footing of hard concrete and the relatively soft ground level for the purpose of preventing a decrease in the ground strength after excavation (which is the work to construct a foundation footing). This construction method has been adopted worldwide, not only in Japan but also in European countries and China, which have a long architectural history. Broken stone and crushed stone are generally used in foundation work. Recently, it has been difficult to obtain high-quality broken stone and the number of skilled workers with experience in broken stone foundations is limited; therefore, the use of crushed stone has become the mainstream (Sato et al., 2002; Fujii et al., 2006). Crushed stone was originally collected as a natural resource, however, it has already been collected to such an extent that environmental destruction has become a concern and the cost of distributing crushed stone is high. Under such circumstances, alternative materials that have a limited burden on the environment have been desired.

Based on the points discussed above, in this study, the production method and basic properties of waste gypsum boards are examined, and the selection of a construction method for foundation work and its applicability are described.

2. Processing of Waste Gypsum Boards into Raw Material

Waste gypsum boards were crushed and the raw gypsum material was separated from the paper. Gypsum at this point is calcium sulfate with two molecules of water of crystallization known as gypsum dihydrate. It loses four-thirds of its water of crystallization by heating at 120 to 150 degrees Celsius. Although the composition implies that it was slightly over-fired, at least 90% of gypsum hemihydrate was obtained. Table 1 shows the results of composition analysis using an X-ray diffractor which can detect a peak value of gypsum dihydrate. Although the composition implies that it was slightly over-fired, it is considered possible to reliably obtain almost 90% of gypsum hemihydrate.

### Table 1. X-ray Diffraction Analysis Results

| Materials/Conditions | Unit | Value |
|----------------------|------|-------|
| Material temp. at the outlet of the calcination furnace | °C | 170 |
| Calcination time | min | 14.3 |
| Gypsum hemihydrate % | | 89.2 |
| Gypsum dihydrate % | | 1.8 |
| Others * | % | 9.1 |

*Sum of the proportions of anhydrate II and Impurities

simplified drying equipment (Yagi et al., 2005). The crushed gypsum specimen is conveyed by a screw conveyor, while the gas-powered infrared burner radiates heat from above to the gypsum particles in transit (Fig.1.). Calcination was performed at two radiation zone temperatures of 130 and 170 degrees Celsius. The crushed stone and crushed stone are generally used in foundation work.

3. Application of Recycled Gypsum to Foundation Work

3.1 Foundation work, a general description

For a broken stone foundation, the use of 120-mm-thick broken stones and 30-mm-thick blinding concrete is specified in the Building Standard Act. However, there are no specifications concerning the properties and nature of the materials or construction methods used (e.g., Sato et al., 2002). Qualitatively, the foundation need not be a consolidated body like concrete and can be an aggregate of rubble, such as broken stones, if the foundation is capable of transferring the load of the upper structure to the lower ground (Yoshida, 1990).

The foundation work is required to provide a wide flat working space where workers can carry out marking and form panel placement in order to obtain a good foundation structure, such as a sleeping foundation. The bearing capacity of the soil or higher is sufficient for the strength of the foundation because the basic load is transferred to the soil. The standard bearing capacity of the soil of a house targeted in this study is 50 kN/m². It is important for the broken stones to compact the surrounding soil by embedding into the excavated bottom with a randomly uneven surface as a result of excavation.

3.2 Recycled gypsum composite mortar (RGCM)

The recycled gypsum composite mortar (RGCM) is produced from the gypsum hemihydrate obtained by recycling waste gypsum boards, slag cement, and waste molding sands (recycled material). When the gypsum hemihydrate is subjected to hydration in the presence of cement, it shows a water hardening property owing to the stimulation of alkali. The strength of the
RGCM depends on the water content, similarly to that in the case of concrete. Table 2. shows a series of physicochemical characteristics for different ratios of water to composite (gypsum + cement) samples which can be available as a self-leveling material (SL material). The composition of samples consists of gypsum, slag cement, and very fine sand at a ratio of 50:20:30. An unconfined compression test was carried out for these cylinder core samples \(d=50 \text{ mm, } h=100 \text{ mm}\) under a constant temperature and relative humidity of 23 degrees and 50%, respectively. When the water/composite ratio is increased, the SL property of the RGCM improves, but its compressive strength decreases (Fig.2.). However, the 28-day strength for the highest water/composite ratio (S-1) is 94 kN/m\(^2\), that can be satisfied with the standard bearing capacity. When the water/composite ratio is less than 50% (S-6), the 28-day strength is 1,580 kN/m\(^2\), the highest strength required for structural members can be obtained.

### 3.3 Durability of RGCM

It has been observed that a gypsum-hardened body is weak in water, which is explained by the fact that the compressive strength of a gypsum-hardened body in water decreases to approximately 40% of that under dry conditions. This decrease in compressive strength can be suppressed and water resistance can be increased when gypsum is mixed with other materials, such as cement and resin.

For a foundation supported by soil, soil dissolution or collapse leads to ground subsidence. Therefore, it is necessary to demonstrate that the foundation material is more resistant to dissolution or collapse than soil. As one of the direct empirical tests, the authors showered two samples with water, i.e., a sample of the loam layer of the Kanto region (collected from Utsunomiya City (Tochigi, Japan), compacted in three layers, and dried for one day), and an RGCM sample (water/composite ratio was 115% (S-2), dried in air for 3 days and then immersed in water for 7 days) to visually observe the dissolution and collapse of these samples. As the water shower condition, 12 L/min of water was used to shower the samples from a height of 50 cm to observe any changes in them.

The results of the test indicate that the Kanto loam sample started to collapse from the top at 30 s from the start of the water shower and then completely collapsed at 90 s (photos 1 a-d). In the case of the RGCM sample, no change was observed at 90 s from the start of the water shower (photos 2 a-d). These results indicate that even a low-strength RGCM used as an SL material is superior to the Kanto loam sample in terms of water resistance and therefore does not dissolve or collapse before the Kanto loam sample.

### 3.4 Flat plate loading test

1) **Methods**

Field measurement for flat plate loading test (JIS

| Sample | PC | water/composite | Flow value | Specific gravity | pH  |
|--------|----|-----------------|------------|-----------------|-----|
| S-1    | 0.0| 131             | 169.5      | 1.40            | 8.0 |
| S-2    | 0.2| 115             | 173.0      | 1.41            | 12.1|
| S-3    | 0.3| 109             | 163.0      | 1.44            | 12.3|
| S-4    | 0.5| 99              | 163.5      | 1.47            | 12.5|
| S-5    | 1.0| 83              | 174.5      | 1.53            | 12.8|
| S-6    | 9.0| 44              | 155.0      | 1.85            | 13.1|

PC: the ratio of cement mixture amount to gypsum amount
A 1215-2001, Method for plate load test on soils for roads) was carried out at Yokohama City (Kanagawa, Japan). Three different types of foundation work, namely i) Kanto loam soil as the original ground (OG), ii) crushed stones with leveling concrete (CSC), and iii) recycled gypsum composite mortar (RGCM), were compared. Fig.3. illustrates each type of foundation work. Swedish sounding was performed before the plate-loading test to confirm the ground structure of the test sites and then all the three sites (OG, CSC, and RGCM) had similar ground structures. Soft cohesive soil with an N value of approximately 3 was distributed to a depth of 0.5-1.5 m from the surface, and the N value increased slightly to 4-5 at a depth of up to 3.0 m, and to 15 or more at a depth greater than 3 m, indicating that the ground was very hard below 3 m from the surface.

The increment of load was 2.5 kN (diameter of loaded plate: 30 cm) and the load was linearly increased to 12.5 kN, which was considered to be the maximum load. The test was carried out to determine the subgrade reaction coefficient k, and the allowable bearing capacity was also measured for reference.

2) Results

Tables 3.-5. show the relationship between settlement and load for the OG, CSC, and RGCM foundation, respectively. The results are compared and shown in Fig.4. The k values were calculated and the allowable bearing capacity values were estimated (Table 6.). The k value in the case of the RGCM foundation is the highest, followed by that in the case of the CSC foundation, and that in the case of OG.

The allowable bearing capacity of the CSC foundation is only used as a reference because the yield point is unclear. In the case of the RGCM, the ground clearly yields. In the case of the CSC foundation, the broken stone layer is considered under the strain hardening condition because the foundation layer is as thick as 150 mm. Under this condition, the relationship between stress and strain is not linear, i.e., the stress peak is not observed even when the strain increases to a relatively high value.

The observed values are calculated by assuming that the diameter of the loaded plate is 30 cm. It is considered that the layer below the RGCM, i.e., the broken stone or original ground layer, rather than the RGCM, is deformed or yields in the case of the RGCM foundation. Therefore, it is better to apply the load to the lower layers through the intermediate foundation layers, rather than to the loading plate. If this assumption is true, it is rational to consider that the diameter of the loaded plate is 33-35 cm (average: 34 cm) rather than 30 cm to compensate for the stress. When the results are reorganized by considering this compensation, the following results are obtained.

After correction, the values other than that for OG slightly decrease; however, the overall trends observed before and after correction are similar. The value for the RGCM foundation is the best when more reliable standards of k are adopted. The increases in the values for the CSC and RGCM foundations from that for OG may be attributed to the effect of foundation layers. The strength (adhesive strength) of the ground is

| Time (min.) | Load Total (kN) | Intensity (kN/m²) | Subsidence Right (Gauge (mm)) | Subsidence Left (Gauge (mm)) | Subsidence Average (Gauge (mm)) |
|-------------|----------------|--------------------|-------------------------------|-------------------------------|-------------------------------|
| 0           | 0              | 0                  | 0.00                          | 0.00                          | 0.00                          |
| 10          | 2.5            | 35                 | 0.90                          | 0.95                          | 0.93                          |
| 20          | 5.0            | 71                 | 1.88                          | 1.62                          | 1.75                          |
| 35          | 7.5            | 106                | 3.43                          | 2.57                          | 3.00                          |
| 50          | 10.0           | 142                | 5.57                          | 4.29                          | 4.93                          |
| 65          | 12.5           | 177                | 9.46                          | —                             | —                             |

Table 4. Plate Load Test Result for CSC

| Time (min.) | Load Total (kN) | Intensity (kN/m²) | Subsidence Right (Gauge (mm)) | Subsidence Left (Gauge (mm)) | Subsidence Average (Gauge (mm)) |
|-------------|----------------|--------------------|-------------------------------|-------------------------------|-------------------------------|
| 0           | 0              | 0                  | 0.00                          | 0.00                          | 0.00                          |
| 10          | 2.5            | 35                 | 0.57                          | 0.41                          | 0.49                          |
| 20          | 5.0            | 71                 | 1.03                          | 0.99                          | 1.01                          |
| 35          | 7.5            | 106                | 1.53                          | 1.67                          | 1.60                          |
| 50          | 10.0           | 142                | 2.07                          | 2.41                          | 2.24                          |
| 65          | 12.5           | 177                | 2.76                          | 3.59                          | 3.17                          |

Table 5. Plate Load Test Result for RGCM
estimated from the allowable bearing capacity of OG (38 kN/m²).

3) Discussion

Formula for bearing capacity for cohesive soil:

\[ q_s = \frac{1}{3}\alpha c N_c \]  \hspace{2cm} (1)

Here, \( \alpha \) is the shape coefficient (1.3 for circular shape), \( c \) is the adhesive strength, and \( N_c \) is the coefficient of bearing capacity (5.3 at \( \phi = 0 \)).

The value that satisfies the above condition is \( c = 17 \text{ kN/m}^2 \). This value is considered to be appropriate, although it is slightly low for the soft cohesive soil with an \( N \) value of approximately 3. In the plate loading test, circular plates with a diameter of 30 cm were used. The shape and size are slightly different from those used in the actual foundation (a continuous strip footing foundation with a thickness of 60 cm at 50 kN/m²). As a result, the depth to which the stress is applied may be shallower.

Overall, the following tendencies are summarized.

a) By packing broken stones (or crushed stones) and RGCM below the foundation footing, \( k \) and bearing capacity tend to increase compared with those of the original ground, indicating the effectiveness of such a packing. However, when the area of the foundation increases, the percentage of the original ground area to which stress is applied increases; the differences in \( k \) and bearing capacity between the original ground and RGCM foundation or CRC foundation slightly decrease.

b) When the CRC foundation and RGCM foundation are compared, \( k \) for the latter is obviously greater than that for the former although the latter foundation is thinner (100 mm thick). The allowable bearing capacity of the latter is considered to be slightly greater than that of the former, considering the transition point from linear to nonlinear regions, although the yield point of the crushed stones with a leveling concrete foundation is not clear.

From the results obtained in this study, the performance of the RGCM foundation was confirmed to be superior to that of the CSC foundation, which is a standard foundation footing specified by the Housing Loan Corporation in Japan.

| Conditions                          | \( k \) value (kgf/cm²/ cm) | Bearing capacity (kN/m²) |
|-------------------------------------|-----------------------------|--------------------------|
| Kanto loam, OG (without foundation) | 4.7 (without correction)    | 38 (without correction)  |
| Crushed stone with leveling concrete (CSC) foundation | 5.4 | 43 (yield point unclear) |
| Recycled gypsum composite mortar (RGCM) foundation | 9.1 | 50 (yield point unclear) |

4. General Discussion

4.1 Various uses of gypsum with cement

Gypsum is highly compatible with cement and is used in the following applications by mixing with cement (e.g., Ando, 1972).

1) Normal cement (Portland cement): Portland cement contains approximately 3.5% gypsum, which plays an important role as a quick-setting inhibitor.

2) Cement-based soil hardener: To improve the quality of the organic soil and the soil with high water content, a cement-based soil hardener, obtained by adding approximately 10% exsiccated gypsum to the cement, is frequently used (Shinohara, 2003).

3) Nonshrinkage cement: Shrinkage cracks are generated when setting large areas because cement shrinks by approximately 7% during setting. To prevent the generation of such shrinkage cracks, gypsum is added to generate ettringite, and shrinkage is prevented.

4) Sulfate slag cement: Sulfate slag cement is mainly made of blast furnace slag and gypsum. When 10-15% gypsum with respect to the total amount of blast furnace slag is added, blast furnace slag hardens with the action of sulfate contained in the gypsum.

As explained above, the advantages of gypsum are exploited in various applications in combination with cement.

4.2 Performance of RGCM foundation

1) Comparison with blinding concrete (e.g., in terms of compressive strength and working load)

The compressive strength of the high water/composite ratio (more than 99%) RGCM foundation is strong enough to support the load of the sleeping foundation. This value is sufficiently large for the bearing capacity of the RGCM. Fujii et al. (2006) suggested that the foundation thickness should be more than 100 mm if the ground has more than 30 kN/m² of bearing capacity. This study showed that the RGCM foundation can provide a superior performance even though its thickness is 100 mm. The hardening surface of the RGCM is smooth and there are no problems related to marking and joinability. There is no requirement for compaction as in the usual foundation process. Also, gypsum does not need long dry curing (Turk and Bounini, 1984). Although the test conditions and procedure for gypsum may differ, a drying time for plaster may be shallower.
removal of free water by oven drying is 2 hours in the United States (ASTM C471) and Spain (UNE 7065), and only 1 hour in Italy (UNI 6782-71(H)). Compared with the CRC foundation, the RGCM foundation can reduce the working period by 3 days.

2) *Comparison with broken or crushed stone foundation* (e.g., in terms of subsidence)

Even when the excavated surface is rough, the gaps can be filled with the RGCM thanks to its high fluidity, which is similar to the SL material. Thus, the RGCM is integrated with the foundation ground, and an effect superior to that of a broken stone or crushed stone foundation can be expected. The broken stone or crushed stone foundation is compacted using rammers. However, a high compaction effect cannot be expected for cohesive soil, because a high pore water pressure is generated by the compaction energy owing to the high saturation level (Oda et al., 1998). In some cases, compaction may decrease the bearing capacity of the ground. Therefore, the ground strength of the broken stones or crushed stone is not always higher than that of the RGCM.

3) *Demand – supply balance of gypsum* (e.g., in terms of material recycling)

Japan phased out natural gypsum production in 1976, and is now recycling byproduct gypsum, that is the chemical end product of industrial processing plants, for wallboard, cement, and plaster. In the 1980’s, she led the world in the technology concerning utilization of byproduct gypsum with a balance between supply and demand (Presseler, 1984). However, countermeasures regarding waste gypsum boards had not been well considered in terms of future prospects. In addition, as it is expected that the amount of waste gypsum board will increase threefold in the future (Gypsum Board Association, 2010), its use as a material for the foundation work of new houses is very significant from the viewpoint of waste management.

If we can use the approximately 800,000 tons/year of waste gypsum board as a material for foundation work, approximately 110,000 new houses can be constructed in one year. Here, calculation was carried out by using the total amount of gypsum boards generated yearly at demolition sites and assuming that one new house (e.g., base area: 100 m², excavation thickness: 320 mm, foundation thickness: 70 mm) requires approximately 5 tons of waste gypsum boards. The total number of newly built single-family houses in Japan is approximately 440,000 tons/year, indicating that the waste gypsum boards generated yearly at demolition sites can be consumed in the foundation work of approximately one-quarter of newly built houses.

5. Conclusion

For a foundation using a recycled gypsum composite mortar (RGCM) that is produced for use as an SL material, and which has enough strength for ease of construction, the $k$ value was greater than that of a broken stone foundation of standard specifications. Foundations are sometimes immersed in water. The water resistance of the RGCM is much higher than that of the Kanto loam foundation, which is considered to indicate its appropriateness for use as a foundation ground for single-family houses. Also, the RGCM foundation is advantageous from the viewpoint of the recyclability of increased waste gypsum in the world.

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