Environment-Conscious Building Materials Comprising Pulverized Plaster Board, Fly Ash and Ground Granulated Blast-Furnace Slag

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ABSTRACT: During 2000, about 950 thousand tons of waste plaster boards (WPBs) were released in Japan. An effective reuse of WPBs is a matter of social concern in Japan. This paper deals with the development of inorganic materials comprising pulverized WPBs (P-WPB: G), fly ash (F) and ground granulated blast-furnace slag (GGBFS: S). The fundamental properties of an F-S-G paste with regard to fluidity, drying shrinkage and compressive strength were tested and the influence of the replacement ratio of pulverized waste gypsum boards (PWGs) were investigated. The test results revealed that the strength of the F-S-G paste increased with the GGBFS content and the replacement of P-WPB slightly decreased the strength after 28 days.

1 INTRODUCTION

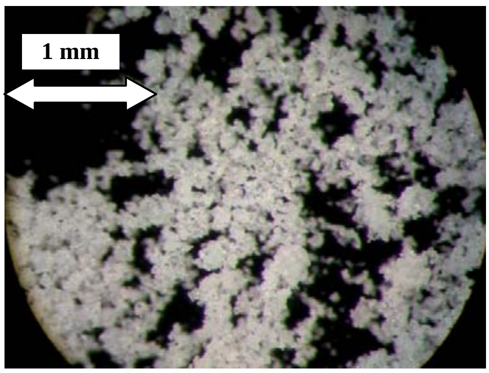
In Japan, about 950 thousand tons of waste plaster boards (WPBs) were released during 2000; this value is estimated to increase up to 1080 thousand tons by 2010. About 40% of WPBs released from building construction sites are reused as additives for new plaster boards, soil improvement materials and so on. An effective reuse of WPBs is a matter of social concern in Japan. One of the methods of reuse is dehydration. Recycled hemihydrates and anhydrous gypsum can be obtained by using wet or dry dehydration [Kojima, Yasue & Arai 1997]. Dehydration can be achieved by using sulphuric acid at 100 ºC for the wet method and by heating at about 200 ºC for the dry method. Both methods have certain issues from the viewpoints of human safety for the wet method and energy consumption for the dry method. On the other hand, previous studies have reported the utilization of pulverized WPBs (P-WPBs) by combining gypsum ($CaSO_4$ $2H_2O$) with ground granulated blast-furnace slag (GGBFS) [Takahashi & Shigekura 1996]. Further, a combination of fly ash, GGBFS and gypsum ($CaSO_4$ $2H_2O$) was investigated in order to diversify the utilization of fly ash [Ishii 2002], [Horii 2005]. The authors aim toward a combination of fly ash (F), GGBFS (S) and P-WPB (G) that will diversify the utilization of P-WPBs with low-energy consumption. This paper describes the fresh and mechanical properties of F-S-G pastes.

2 OUTLINE OF EXPERIMENTS

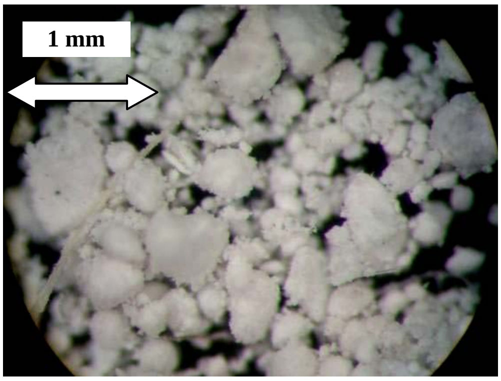
2.1 *Preliminary test*

An optical microscope is used to observe the appearances of the P-WPB and reference gypsum available in the market (photographs 1, 2 and 3). Gypsum available in the market (reference gypsum) exhibits fine uniform particles, as shown in photograph 1. P-WPB is obtained by crushing and stepwise grindings of PWBs such that they can pass through a sieve size of 0.5 mm. Photograph 2 shows that the P-WPB consists of irregular particles. Photograph 3 shows paper fibres present in the P-WPB. Grading curves of P-WPB and reference gypsum are shown in Fig.1. A sieve analysis shows that the P-WPB has coarser particles than reference gypsum.

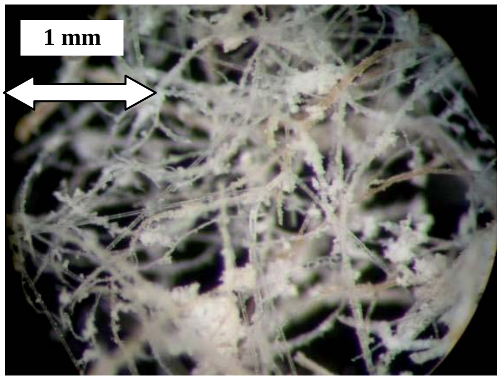
In order to accelerate the hardening of the G-S-F paste, an alkaline stimulus agent should be added. In this study, Ordinary Portland Cement (JIS R 5210) and $CaOH_2$ are examined to function as the stimulus agent. Specimens with dimensions of 4 × 4 × 16 mm and a water-to-powder (G: 20%, S: 20% and F: 60%) ratio of 0.4 were prepared; here, the amount of stimulus agents in the powder ranged from 0 to 5% by mass. Test results of the compressive strength obtained after a period of four days are shown in Fig.2. It can be seen that F-S-Gs with Ordinary Portland Cement exhibit greater strength than those with $CaOH_2$. Hence, Ordinary Portland Cement (3% by mass) was adopted as the stimulus agent in this study.



Photograph 1. Appearance of reference gypsum



Photograph 2. Appearance of P-WPB



Photograph 3. Appearance of paper fibres present in P-WPB

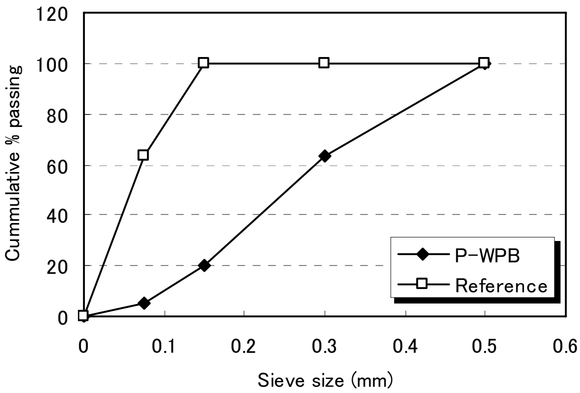


Figure 1. Grading curves of reference gypsum and P-WPB

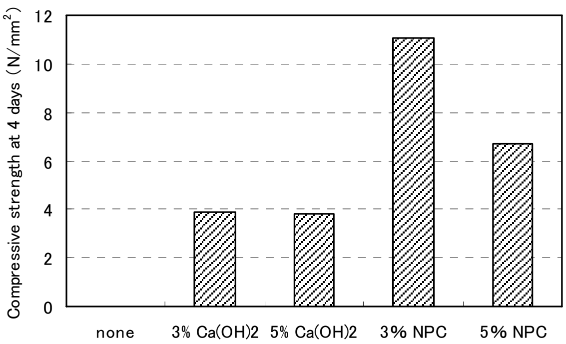


Figure 2. Compressive strength of F-S-G with stimulus agent

2.2 *Materials used and mixture proportions*

The properties and chemical compositions of materials used and mixture proportions are listed in tables 1, 2 and 3, respectively. The chemical compositions were determined by X-ray fluorescence spectrometric analysis. Mixing was carried out using a mortar mixer with a special paddle to uniformly disperse the particles. Water to powder (except cement as stimulus agent) ratio is 0.4. Stimulus agent (Ordinary Portland Cement) of 3 % by mass was added to the mixtures prior to the mixing. A triangle diagram comprising F, S and G is shown in Fig.3. For example, 'No.5' denotes the mixture proportion of 40% with fly ash (F); 20%, GGBFS (S); and 40%, gypsum (G). Replacement ratios of P-WPB for the reference gypsum are 0% (without P-WPB), 20%, 50% and 100% (without reference gypsum). In this study, 60 mixtures were prepared, as listed in table 3.

Table 1. Materials used

Material	Properties
Fly ash (F)	Density: 2.24g/cm^3; specific surface area: 3430 cm^2/g
GGBFS (S)	Density: 2.86 g/cm^3; specific surface area: 4830 cm^2/g
Reference gypsum	Density: 2.34 g/cm^3; length: 200 μm; width: 20 μm; pH: 8.76*
P-WPB	Density: 2.19 g/cm^3; pH: 6.79*
Stimulus agent	Ordinary Portland Cement with a density of 3.16 g/cm^3

*Concentration of 10% by mass at 20 ºC

Table 2. Chemical compositions of materials

Composition (%)	Mg	Al	Si	S	Ca	Ti	Fe	Others
Fly ash (F)	0.9	24.0	60.3	0.4	3.5	1.8	3.6	5.4
GGBFS (S)	6.2	11.6	25.5	2.1	52.2	1.6	0.3	0.6
Ref. gypsum	-	-	0.3	42.0	57.7	-	-	0.1
P-WPB	-	0.4	0.6	45.7	52.8	-	0.5	0.1

Table 3. Mixture proportions (wt %)

No.	F	S	G	Replacement ratio of P-WPB			
1	80	10	10				
2	60	20	20				
3	50	10	40				
4	50	40	10				
5	40	20	40				
6	40	40	20				
7	30	10	60				
8	30	60	10	0	20	50	100
9	20	20	60				
10	20	40	40				
11	20	60	20				
12	10	10	80				
13	10	30	60				
14	10	60	30				
15	10	80	10				

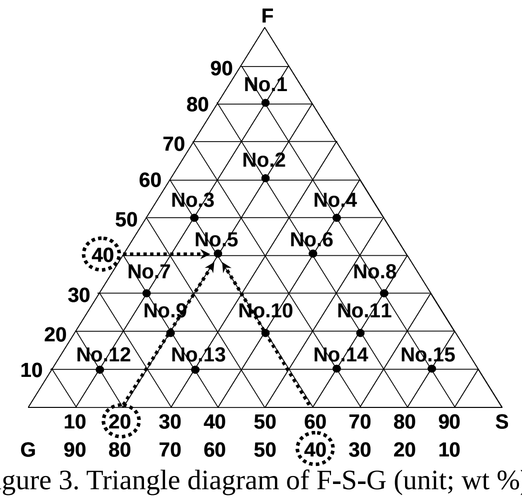


Figure 3. Triangle diagram of F-S-G (unit; wt %)

3 TEST RESULTS AND DISCUSSIONS

3.1 *Fluidity*

Flow tests were carried out according to the JIS R 5201 standard, as shown in Photograph 4. Mixtures without P-WPB conform to a flow of 20 cm, which is estimated to be workable. Fig.4 shows that the increases in the replacement ratios of P-WPB contract the workable areas due to the irregular particle shapes and the presence of fibres, as shown in photographs 2 and 3. It should be noted that the workable area shifts to the upper region of the diagram, where a high content of fly ash is used. The round particle shapes of fly ash, as shown in Fig. 4, have a ball-bearing effect and contribute to the fluidity of the G-S-F paste with a high replacement ratio of P-WPB. From the viewpoint of workability, the utilization of fly ash is effective when a large amount of P-WPBs is used.

Photograph 4. Device for flow test

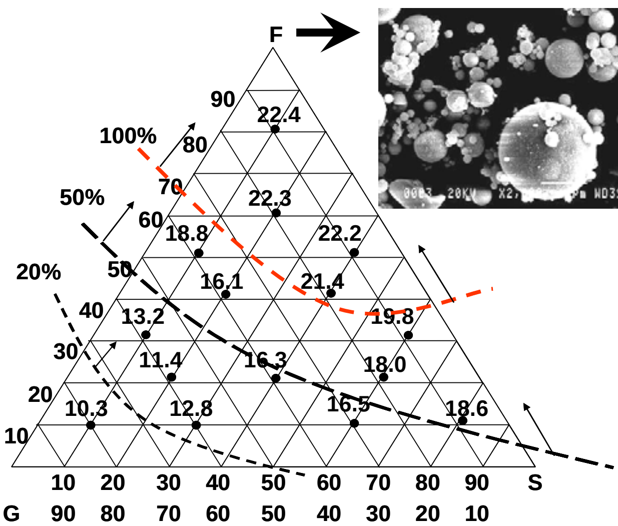


Figure 4. Fluidity map of F-S-G

3.2 *Drying shrinkage*

Drying shrinkage strains were measured in accordance with the JIS A 1129 standard. A specimen with dimensions of 4 × 4 × 16 mm was cured in water at 20 ºC before drying was initiated. Fig.5 shows the test results obtained 91 days after drying; the P-PWB replacement ratios are 0% and 100% (brackets). F-S-Gs with a high content of GGBFS (S) tend to exhibit a large shrinkage strain, and F-S-Gs with a high content of fly ash exhibit a smaller strain. The drying shrinkage strain for F-S-Gs with a fly ash content of 80% by mass is below 1000 micro–strain; this combination can be used as materials with low shrinkage instead of cement (normally exhibits about 2000 micro-strain). The use of fly ash is effective in the prevention of shrinkage-induced cracking and unexpected deformation of the pastes. Further, it can be seen that the replacement ratio of P-PWB has no significant influence on the drying shrinkage of the F-S-G paste.

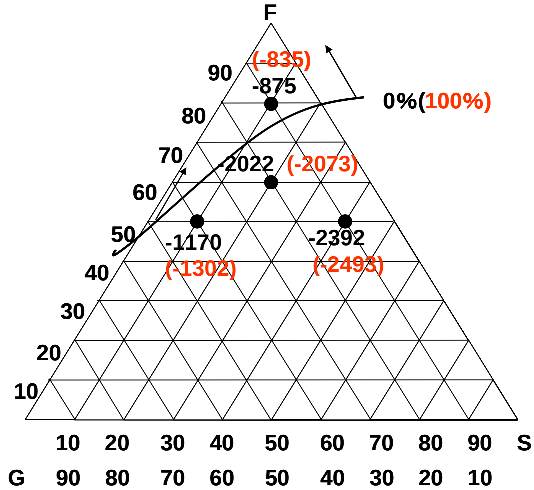


Figure 5. Drying shrinkage map of F-S-G

3.3 *Unit weight*

The unit weight was measured in accordance with the JIS R 5201 standard. Specimens obtained 91 days after drying were used for the measurements. The test results are shown in Fig.6; P-PWB replacement ratios are 0% and 100% (brackets). In the measurement calculations, air content of the specimen is included. The specimens with a unit weight of less than 1.5 g/cm^3 are placed in the left region of the figure. Portability is one of the advantages of building materials. Lightweight F-S-G pastes (less than 1.5 g/cm^3) might be useful as indoor building materials. Further, low unit weight materials have porous microstructures and hence the paste can be applied to humidity-control-type building materials with low shrinkage deformation. Evidently, F-S-Gs with a high content of P-PWBs contribute toward the reusability efficiency. It can be seen that the unit weight of F-S-Gs is independent of the replacement ratios of P-WPBs.

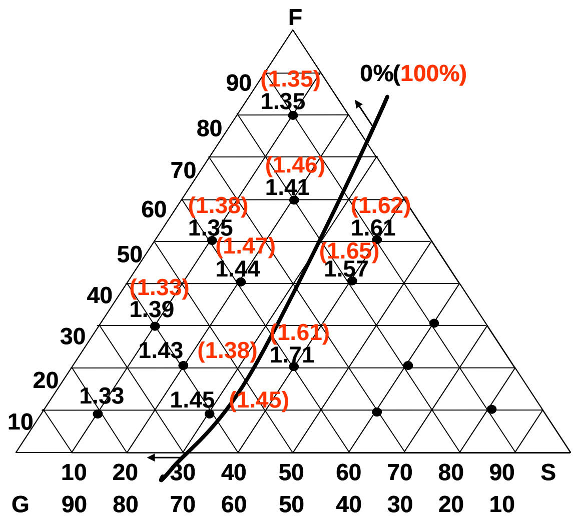


Figure 6. Unit weight map of F-S-G

3.4 *Compressive strength*

The compressive strengths of F-S-G pastes with dimensions of 4 × 4 ×4 cm were tested in accordance with the JIS R 5201 standard. The test results obtained at 28 days are shown in Fig.7; P-WPB replacement ratios are 0% and 100% (brackets).

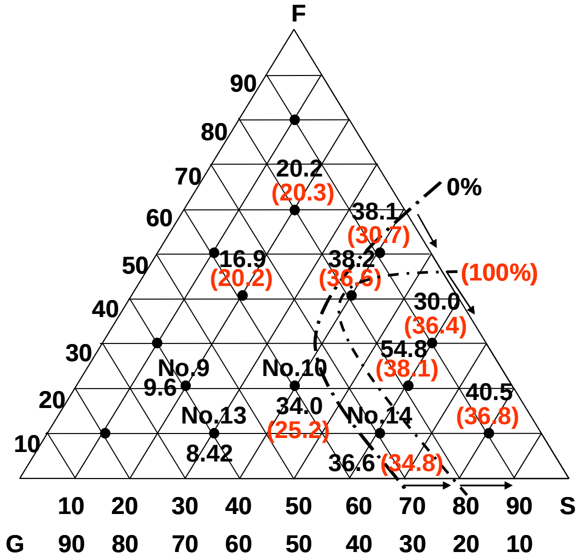


Figure 7. Compressive strength map of F-S-G

Mixtures with high strengths are placed in the right region of the figure where a large amount of GGBFS (S) is used. The strength of F-S-G strongly depends on the amount of GGBFS. In the figure, the dotted lines represent the region with compressive strengths of 35 N/mm^2. The replacement of P-WPB slightly contracts the abovementioned region. It can be seen that the strengths of No.10 and No.14 are considerably greater than those of No.9 and No.13, as shown in Fig. 7.

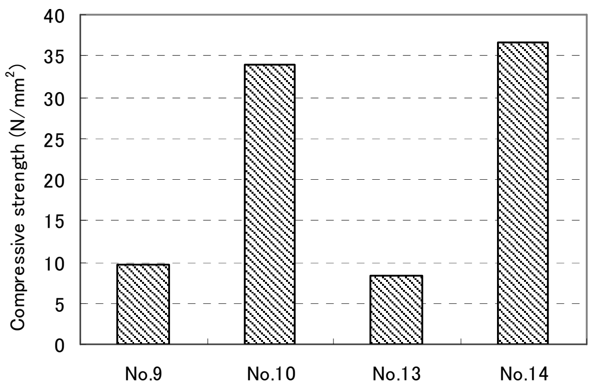
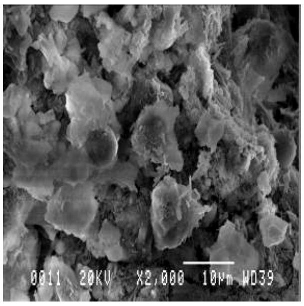


Figure 7. Compressive strength of F-S-G paste

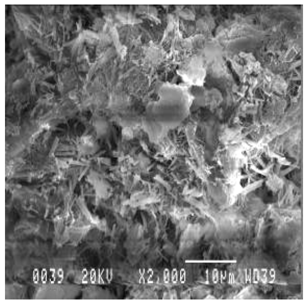
3.5 *Microstructures of F-S-G pastes*

A scanning electron microscope (photograph 5) is used to visualize the rough and porous structures of No.9 and No.13 and the smooth and dense structures of No.10 and No.14, as shown in Photograph 6. Mercury intrusion porosimetry (photograph 7) provides microstructural information about the F-S-G paste, as shown in Fig.8. Fig.9 shows that an increase in the total pore volume of the F-S-G paste decreases the compressive strength of the paste at 28 days as well as that in cementitious materials. XRD diffraction analysis is used to detect the existence of gypsum ($CaSO_4$ $2H_2O$) and ettringite ($3CaO$ Al_2O_3 $3CaSO_4$ $32H_2O$) in the pastes. Fig.10 shows that gypsum peaks are observed particularly in No.9 and No.13 when compared with those in No.10 and No.14. These results indicate that un-hydrated gypsum that remains in the F-S-G paste cause a decrease in strength. A content ratio of less than about 40% by mass of P-WPB in the F-S-G mixture is appropriate from the viewpoint of strength.

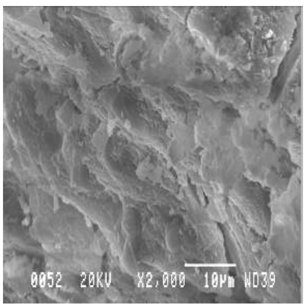
Photograph 5. Scanning electron microscope (SEM)



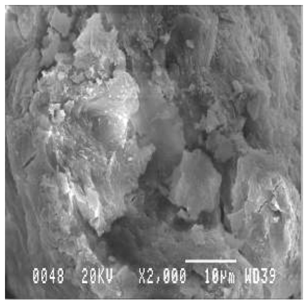
No.9 (F:S:G=20:20:60)
Comp. strength 9.6N/mm^2



No.13 (F:S:G=10:30:60)
Comp. strength 8.4N/mm^2



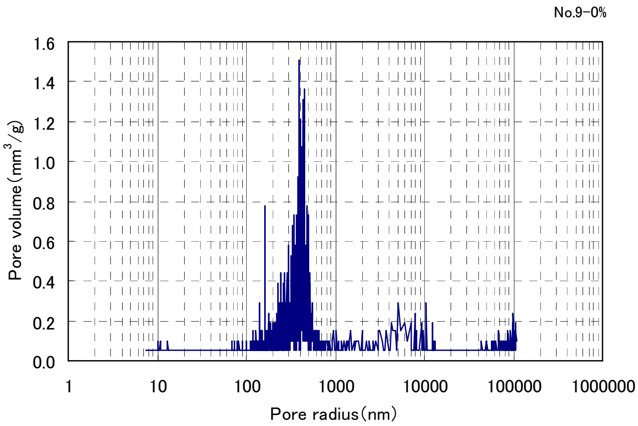
No.10 (F:S:G=20:40:40)
Comp. strength 34.0N/mm^2



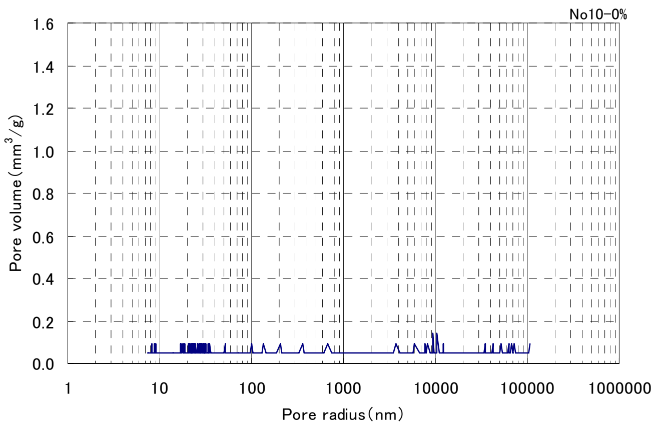
No.14 (F:S:G=10:60:30)
Comp. strength 36.6N/mm^2

Photograph 6. Appearances of F-S-G pastes

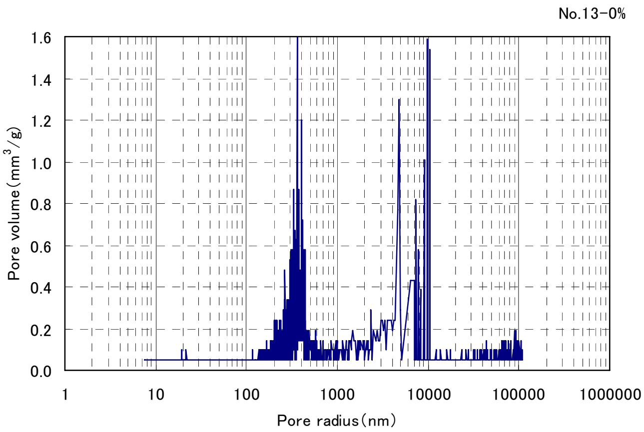
Photograph 7. Device for mercury intrusion porosimetry



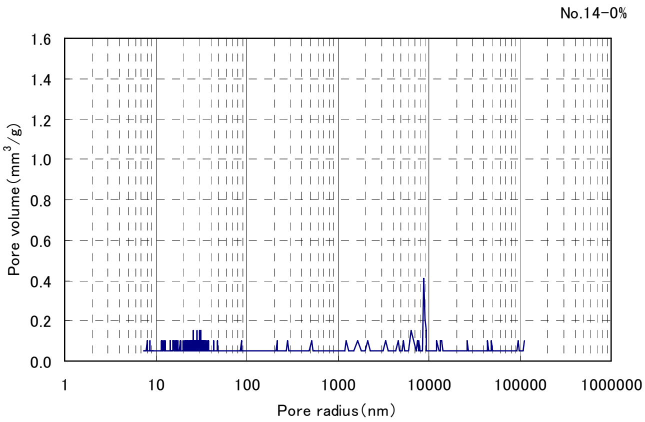
(a) No.9



(b) No.10



(c) No.13



(d) No.14

Figure 8. Pore size distribution of F-S-G pastes

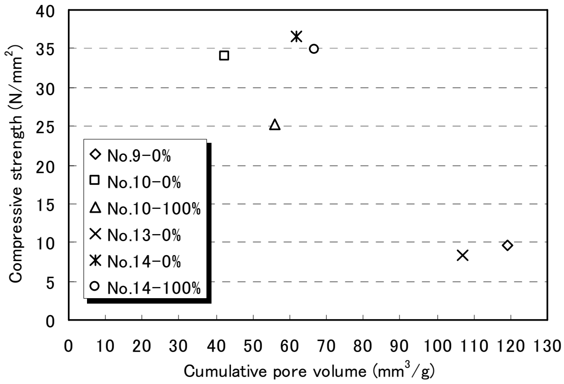


Figure 9. Total pore volume versus composite strength of F-S-G paste

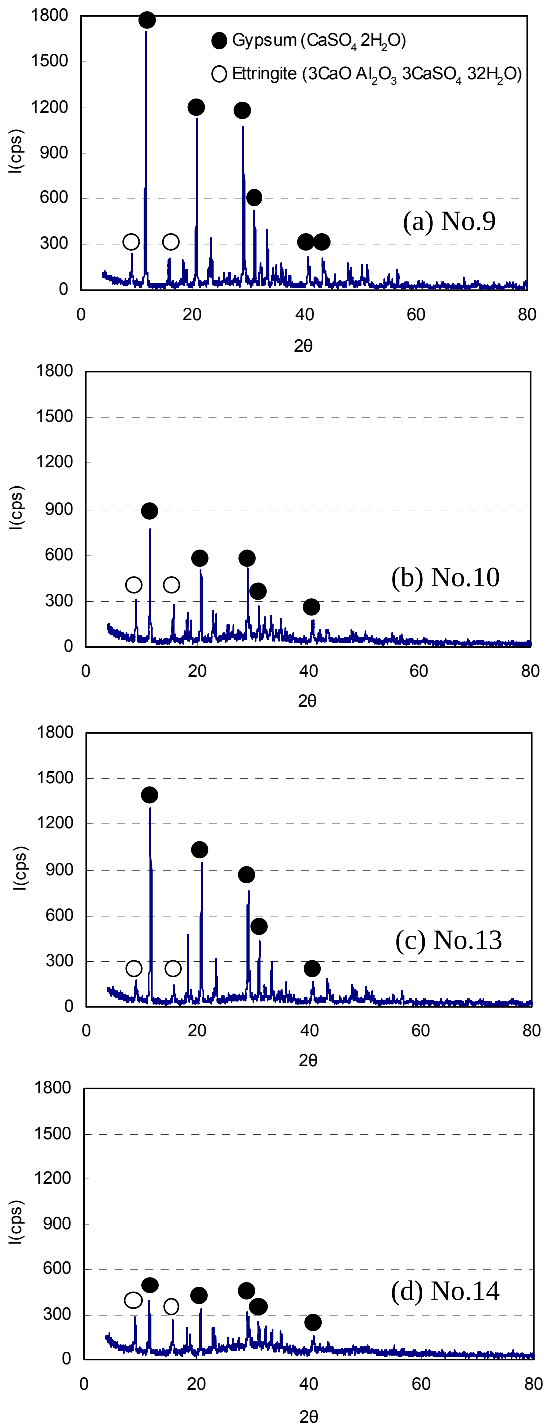


Figure 10. XRD diffraction analysis for F-S-G pastes

In order to recover the decreased strengths of No.10 and No.14 by using 100% P-WPB, a controlled P-WPB with the same cumulative percentage passing curve as the reference gypsum was prepared (Fig.1). The flow and the compressive strength tests conducted at 28 days are shown in Figs.11 and 12, respectively. It can be seen that the strength with controlled P-WPB is close to that with reference gypsum. The controlled grading of P-WPB is effective in improving the strength of F-S-G pastes; however, flows in the fresh state decrease significantly, as shown in Fig.11. Further studies to satisfy both these performance criteria are required.

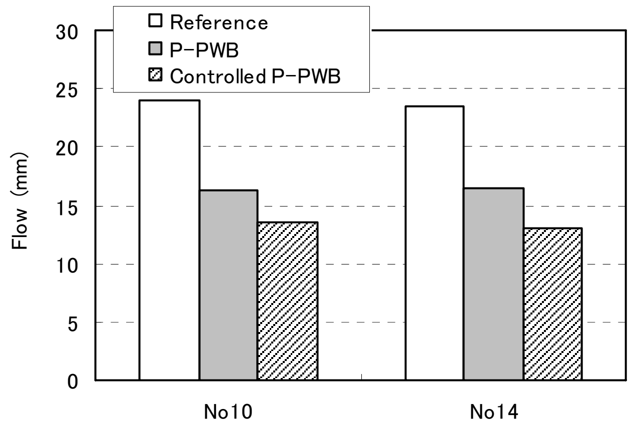


Figure 11. Flow of F-S-G with controlled grading of P-PWB

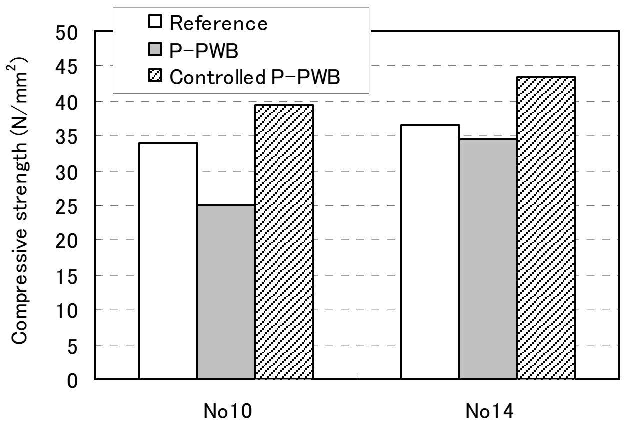


Figure 12. Compressive strength of F-S-G with controlled grading of P-PWB.

4 CONCLUDING REMARKS

This study aims to utilize P-WPBs (G) along with a combination of fly ash (F) and GGBFS (S).

The following conclusions were obtained in this study:

1) Increase in the replacement ratio of P-WPB tends to decrease the fluidity of the F-S-G paste. Fly ash contributes to fluidity by inducing the ball-bearing effect.
2) Using fly ash decreases the drying shrinkage strain of the F-S-G paste. The replacement of P-WPB has an insignificant influence on the magnitude of the shrinkage strain of the paste.
3) Compressive strength of the F-S-G paste strongly depends on the amount of GGBFS. The replacement of P-PWB slightly decreases the strength at 28 days. From the viewpoint of mechanical performance, the gypsum content should be less than 40% by mass for the powder.

5 FUTURE OVERVIEW

F-S-G pastes with P-WPB exhibit various performances with regard to fluidity, drying shrinkage, unit weight and compressive strength. The performance of F-S-G pastes can be controlled by means of its mixture proportion. The F-S-G paste produced from P-WPB and other by-products can contribute to the development of environment- friendly and multifunctional building materials, as shown schematically in Fig.13.

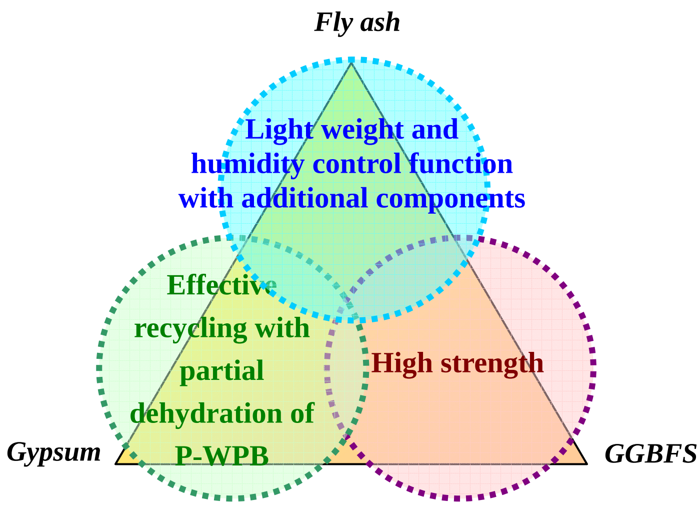


Figure 13. Schematic drawing of environment-friendly and multifunctional building materials

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