Performance of concrete containing silica fume

Fresh concrete

Since silica fume is ultrafine powder, when it is mixed with concrete the viscosity of the concrete increases and flowability decreases, resulting in reduced concrete slump. Thus, the water content necessary to obtain the desired slump increases(14). This can be prevented through use of a superplasiticizer. In other words, the use of silica fume as admixture is not possible without superplasticizer.

With regard to the air entrainment, due to the presence of carbon and ultrafine nature of silica fume powder, air entrainment tends to be difficult, and therefore, with the increase of silica fume content (SF/(C+SF)), the amount of air entraining agent needs to be increased(Fig. 6). Also, with the increase of silica fume content, the segregation tendency in fresh concrete becomes less. When the silica fume content is 10% or higher, neither material segregation nor bleeding occurs even when the slump is 15~20cm(16). It is reported that concrete containing silica fume is vulnerable to plastic shrinkage cracking, therefore, sheet or mat curing should be considered. As shown in Fig. 7, addition of silica fume promotes heat generation at the initial stage of hydration(17). It is reported however that the total amount of heat generated by silica-fume concrete is less than that of ordinary concrete for two days .

Hardened concrete

Mortar and concrete containing silica fume show outstanding characteristics in the development of strength. Fig. 8 shows an example; compressive strength of 60~80Mpa can be obtained relatively easily, although these values may differ depending on the kinds of silica fume and cement, content of silica fume, and curing method and age(18). This property is explained as resulting from the decrease in the volume of large pores in concrete, hence making the concrete texture dense. When accelerated curing such as steam curing and autoclave curing are utilized(Fig. 9), the use of silica fume is also effective in facilitating the development of strength at early age, since the pore size distribution and pore volume significantly differ from those of concrete subjected to standard curing. In such a case, it is verified that compressive strength of 150MPa can be obtained(19). As is shown in Fig. 10, the Young's modulus of elasticity of silica-fume concrete is smaller than that of concrete without silica fume, at the same level of compressive strength. This is because the content of cement paste, which has a lower Young's modulus of elasticity than aggregate increases due to the addition of silica fume.

Durability

As a result of a thorough review of previously published reports, the durability aspect of the concrete containing silica fume are shown in Table 3. The table denotes the number of reports reviewed dealing with the contribution of silica fume to improvement of resistance to frost damage, carbonation, etc., and whether or not the use of silica fume was effective. According to Table 3, effects of silica fume include improved resistance to infiltration of chloride, and increase in electric resistance, watertightness and airtightness. Contradictory data are reported on the effect of silica fume on resistance to frost damage and suppression of alkali-aggregate reaction, as discussed below.

Many studies have been carried out on the resistance of concrete containing silica fume to frost damage, and some of the conclusions contradict each other. Approximately 60% of these reports conclude that the silica-fume concrete offers higher resistance to frost damage than concrete without silica fume, 10~20% conclude that both offer the same level of resistance, and 20~30% conclude that the resistance offered by silica-fume concrete is lower. From Japan and the Scandinavian countries, there are many reports concluding that silica fume contribute to improving the resistance to frost damage, while many reports from Canada conclude the opposite. This discrepancy is attributable to the fact that the evaluation procedure can differ depending on the target of observation, such as, between the case where scaling degradation on the surface is mainly observed and the case where cracks developing on the surface and inside the concrete are mainly observed. Other factors responsible for the discrepancy include differences in the kinds of silica fume, silica fume content, air content and concrete mix proportions. At present, an appropriate amount of entrained air must be supplied irrespective of the concrete mix proportion, conforming to recommendations by the ACI Committee 226 (21) and Canadian Standards Association(22).

With regard to whether or not silica fume is effective for the suppression of alkali-aggregate reaction, some researchers report that it is effective, others conclude that while it is effective, addition of silica fume in small quantities actually increases the expansion. Some researchers indicate that effects vary depending on the kind of silica fume and the type of reactive aggregate. In conclusion, the use of fly ash and blast-furnace slag seems to be more appropriate for this purpose especially because silica fume also happens to be relatively more expensive.

RICE HUSK ASH

Rice husk ash (called rice hull ash in the United States), as indicated by its name, is obtained by burning rice husks. Although ashes can be obtained by burning various kinds of grain husks and straws, rice husk ash has the largest SiO_2 content, and when properly burnt, it can be highly utilized as a concrete admixture. Like silica fume, rice husk ash exhibits highly pozzolanic characteristic and contributes to high strength and high impermeability of concrete(7).

Earlier rice husks used to be burnt in rice paddy farms. However, open-field burning of rice husks causes air pollution, and it is now required that they be burnt at well-managed facilities.

Characteristics of rice husk ash

In the beginning, since temperature control was not adequate, ashes produced contained a large amount of residual carbon, and the amorphous silica content was low. Ashes of this type were effective as concrete admixtures utilized only if steam curing was employed at factories(23). However, in 1972, Mehta(24) reported that the amorphous content of silica in rice husk is considerably affected not only by burning temperature but also by cooling conditions. Subsequent studies conducted at the University of California revealed that amorphous rice husk ash exhibited excellent pozzolanic characteristics even when used in products without steam curing.
As described above, physical properties of rice husk ash are greatly affected by burning conditions. When the combustion is incomplete, a large amount of unburnt carbon is contained in the ash and it presents a blackish color. However, when combustion is complete, gray to whitish ash is obtained, although the gradation depends on the kind and maturity of rice husk as well as on the method of burning. It is also verified that the amorphous content depends on burning temperature and holding time. According to the report from the University of California, optimum properties can be attained when rice husks are burnt at 500~700^{o}C and held for a long time, or when they are burnt at a higher temperature of 700~800^{o}C and held for a short time. In case, however, they are burnt at a temperature higher than 800^{o}C, specific surface area drastically decreases due to the sintering effect as shown in Table 4.

The chemical composition of the rice husk ash produced by utilizing the fluidized bed type furnace is reported to be: SiO_2 80~95%, K_2O 1~2% and unburnt carbon 3~18%. However, the high-carbon rice husk ash samples were found to exhibit pozzolanic characteristics identical to those of the low-carbon rice husk ash samples(26).

Performance of concrete containing rice husk ash

The pozzolanic activity of rice husk ash is not only effective in strengthening the concrete, but also in increasing the resistance to chloride penetration, as shown in Table 5. However, Mehta pointed out in his recent report(26) that not only at low water-cement ratio, but also at high water-cement ratio, the use of rice husk ash is very effective to improve impermeability. With 15% rice husk ash addition (by weight of cement), the chloride permeability with the 0.7 W/C concrete was reduced from 9910 to 1630 coulombs, and with the 0.5 W/C concrete it was reduced from 6860 to 1100 coulombs. Thus, the use of rice husk ash as an admixture for commonly used concrete appears to provide simple and economic approach for making durable concrete structures in the future.

Beside use as admixture, various applications of rice husk ash in concrete have been studied. Applications to roofing(27) and roller compacted concrete(28) have already been reported. However, further studies must be awaited before practical application in industrial products is realized. .

GROUND GRANULATED BLAST-FURNACE SLAG

Blast furnace slag is a by-product of pig iron manufacture. When quenched rapidly with water or air to a glassy state and finely ground, it develops the property of latent hydraulicity. Conventionally, rapidly cooled blast furnance slag is ground simultaneously with cement clinker, or separately ground and then mixed with cement, and marketed as "Blast-furnace slag cement". Since it has hydraulic characteristics, ground granulated blast-furnace slag can also be used as a mineral admixture in concrete.

Ground granulated blast-furnace slag has chemical components similar to that of Portland cement. Due to hydraulicity, therefore, its use contributes not only to improvement in concrete performance, but also to resource and energy savings. The first ground granulated blast-furnace slag, as an industrial product, was produced in Germany in 1923, and was called Thurament.

Characteristics of ground granulated blast-furnace slag

The chemical composition of ground granulated blast-furnace slag is the same as that of blast-furnace slag since it is produced by pulverizing blast-furnace slag. However, in some cases, different values are obtained when a small amount of gypsum has been added.
Table 6 shows the physical-chemical requirements for ground granulated blast-furnace slag in various countries(29). Major chemical constituents are SiO_2: 30~35%, Al_2O_3: 12~15%, CaO: 40~43%, and MgO: 5~10%; minor constituents are Fe_2O_3, MnO, SO_3, TiO_2 and Na_2O. The Japanese Standard Specification contains basicity $(CaO+MgO+Al_2O_3)/SiO_2$, as an index of the activity of blast-furnace slag. Generally higher values than the minimum specified value (1.4) are obtained, indicating the high activity of Japanese blast-furnace slag.

The specific gravity of slag is approximately 2.9, which is slightly lower than that of cement, but higher than that of fly ash; hence, material segregation is less likely to occur in slag-cement blends.

Typically, the fineness of blast-furnace slag is 3000~4000cm^2/g (Blaine). Since finer the slag powder, the greater the hydraulic activity, ultrafine powders with fineness of 6000 to 8000cm^2/g, or even higher are being used in many countries(30).

Performance of concrete containing ground granulated blast-furnace slag

Fresh concrete

When a part of cement is replaced with ground granulated blast-furnace slag, the characteristics of the concrete are naturally affected by the fineness of the ground granulated blast-furnace slag, and its replacement ratio.

Fig. 11 and 12 show the results of the experiment examining the effects of the use of ground granulated blast-furnace slag on the workability of concrete. The unit water content necessary to obtain the same slump decreases with the increase in the slag content(31), and also the fineness of slag(32). This is because the surface configuration and particle shape of slag powder are different than those of cement. In addition, water used for mixing is not easily adsorbed by slag particles since the reaction rate of slag is slower than that of cement.

The bleeding-suppression effect is negligible with slag powder of 4000cm^2/g fineness. However, a significant beneficial effect is observed with slag powders of 6000 and 8000cm^2/g fineness.

Hardened concrete

It has been shown that slag substitution for cement is responsible for the delay in the development of initial strength, and the effect is especially large when the concrete mixture is maintained at a lower temperature.
Heat of hydration of concrete containing slag powder decreases with the increase in the slag powder content. However, when curing is performed at higher temperatures (30^{o}C or higher), there may not be any reduction in the heat of hydration; in fact, the heat of hydration may be greater in the case where slag powder is not added (Fig. 13) when the slag powder content is 50% or less. The heat of hydration is also affected by the fineness of slag powder, gypsum content, basicity, and amorphousness of slag. Generally, when these values are low, the heat of hydration decreases. However, it has been proven that the effects of slag powder and curing temperature are much greater. As shown in Fig. 14, the rate of adiabatic temperature rise of concrete containing slag powder decreases when the slag content is 70% or less, but the ultimate value of adiabatic temperature rise is equivalent to or higher than the case when no slag is added(33). However, when the slag content is 90%, the value tends to decrease

by a large amount.

Durability
Concrete containing slag as a mineral admixtures generally offers better chemical resistance due to improved watertightness, since the concrete texture becomes dense. Slag is also useful for the prevention of corrosion of reinforcement, since it suppresses the infiltration of chlorine ions. The alkali-aggregate reaction can be suppressed by the use of concrete with higher slag powder content as shown in Fig. 15.

Table 7 shows the effects of different combinations of fineness and slag powder content on properties of concrete.

CURRENT STATUS OF MINERAL ADMITURES IN JAPAN AND FUTURE OUTLOOK

In the previous sections, mineral admixtures for concrete currently in wide use are described. In this section, usage of some noteworthy applications in Japan and the future outlook for mineral admixtures will be presented.

First, the author would like to discuss, the ultralow-heat-type cement, which is being utilized in the concrete used for anchorages and piers of Akashi Kaikyo Bridge (3-span suspension bridge,total length 3,900m, central span 1,990m). The Honshu Shikoku Bridge Authority has overseen the construction of many large-scale bridges besides the Akashi Kaikyo Bridge. In the construction of these bridges, they took measures such as the use of low-heat cement, precooling, and post-cooling to avoid the development of thermal cracking in mass concrete. In most cases, however, thermal cracks due to the heat of hydration of cement were observed at anchorages and piers. These thermal cracks do not pose serious problem from the view point of concrete strength since the cracks are small. However, from the viewpoint of aesthetic beauty and long-term durability, it is desirable to prevent development of these thermal cracks. This has led to the development of ultra low-heat-type cement with sufficient initial strength. The Honshu Shikoku Bridge Authority specified a standard concrete mix for construction and contracted cement manufacturers to develop cement which satisfied the requirements of concrete strength and adiabatic temperature rise (Table 8).

Cement manufacturers conducted studies aiming to develop a cement meeting the above described conditions, by blending ground granulated blast-furnace slag, fly ash and cement clinker. As a result, the two-component and three-component cements listed in Table 9 have been developed.
Presently, construction of the pier has already been completed using this type of

cement for both underwater and above-water structures. Construction of the anchorage has also been proceeding steadily and will soon be completed. Development of thermal cracks is very rare, due to the use of the ultra low-heat-type cement. However, concrete made of this type of cement may be neutralized in a short time, and may have poor durability. Therefore, precast concrete facing panels made of polymer impregnated concrete are used for the above-water pier structure, and precast concrete panels made of reinforced concrete are used for the above-water anchorage structure, so that the bulk concrete is not directly exposed to the atmosphere.
In the next step, use of clinker of Berite-based cement, in which C_2S content in cement clinker is higher than 50%, was considered to be a practical means of slowing the neutralization of concrete, and several cement manufacturers began producing Berite-based cement. Composite cement with 30% fly ash and slag powder content each, added to the Berite cement has already been put into practical application as ultralow-heat-type cement, which provides reasonable temperature rise(Fig. 16), and initial strength(Fig. 17).

Second, the author would like to describe the use of a large amount of mineral admixture with the expectation of benefiting from its effect as a fine powder rather than that as a cementing material. In the construction of reinforced concrete, when reinforcement is very closely arranged, especially when a sheath for the prestressed concrete steel strand is also present, it may be difficult to completely fill the voids with concrete. In this case, high-fluidity concrete was developed (with a slump of 25cm or larger) which can fill space by its own weight, and consolidation of concrete by means of a vibrator is not needed. When this type of high-fluidity concrete is placed, generally, material segregation and bleeding develop. Countermeasures for these problems include the increase of the fines in the concrete mixture, use of thickening agents or combination of both. In all the cases, increase of water content is prevented through the use of a superplasiticizer. Addition of a large amount of fly ash or ground granulated blast-furnace slag, for the purpose of increasing the fines, also results in improved long-term strength and lower heat of hydration. When a high long-term strength is not particularly desired, limestone powder is utilized. Limestone powder of 5000~7000 cm^2/g is available commerically, and the fineness can be selected depending on the fineness of cement(37).

Lastly, the author would like to describe a historical structure containing a natural mineral admixture. Approximately 100 years ago, the first ocean breakwater in Japan was constructed at Otaru Port, Hokkaido, Japan. Learning a lesson from the development of cracks in concrete blocks at Yokohama and Kobe Ports, Isamu Hiroi, the first Director of the Otaru Port Authority proposed the use of pozzolanic material together with cement. Volcanic ash was used as an admixture for concrete in the structure, and at the same time, 60,000 mortar briquette specimens were fabricated using different combinations of various kinds of cement, volcanic ash and curing methods, and the long-term testing of these specimens was undertaken. The fabrication of specimens was initiated in 1896, a year preceding the construction of the breakwater at Otaru Port, and continued until 1937. Under the Chairmanship of the author, a committee on Otaru Port concrete durability has recently tested the cores obtained from the 100-year old structure. The results have ensured the long-term stability of the breakwater(38). It is noteworthy that an appropriate evaluation of the use of mineral admixture was made 100 years ago, and a long-term testing program was pursued.

Judging from the conditions under which various mineral admixtures described above were used, the author will forecast the future of mineral admixtures as follows. Strength, durability and fluidity are among the three important areas of concrete performance. Without any doubt, it is the cement matrix which has the greatest influence on these major characteristics of concrete. Materials affecting the physical properties of cement matrix are cement, mineral admixtures and chemical admixtures. Conventionally, in most cases, mineral admixtures were used with the aim of reducing the concrete price. However, in the future, by-product mineral admixtures will be utilized with the aim of improving concrete performance. Increasing use of new admixtures, such as rice husk ash and ultra-low-heat blends is anticipated, and at the same time, the level of expertise of the engineers who utilize them at the construction site must also be raised.

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