Air-Enhanced Self-compactability of Fresh Concrete

論 文 内 容 の 要 旨

This dissertation consists of 7 chapters. Introduction and the originality of research are described in chapter 2 and chapter 3 respectively.　There are 2 sections of experiment were performed which are experiment of mortar and concrete at fresh stage and hardened stage. In experiment on fresh properties, 3 subchapters are presented which are chapter 3: Importance of mortar experiment, chapter 4: Factors affecting flowability and self-compactability of fresh mortar and concrete and chapter 5:Air-enhanced self-compactability of fresh concrete. Characteristic of entrained bubbles is presented in chapter 6 which is the experiment on hardened property of mortar and concrete. Finally, conclusions are written in chapter 7.

Chapter 1 Introduction

Self-compacting concrete (SCC) is well-known as high performance concrete that can flow by its own weight and also has compressive strength approximately 60-70 MPa at 28 days which is very high, compared to conventional concrete. However unit cost of SCC is also very high which is approximately 2 times higher than that of conventional concrete because of higher unit cement content in mix proportion. SCC needs pushing forces between cement particles which is occurred by the reaction between cement particles and superplasticizer thus high amount of cement is necessary for SCC. Self-compacting concrete has not been extensively used in general construction project because of its high cost. Presently, Semi-SCC which is SCC with moderate self-compactability has been created in order to reduce unit cost of SCC by reducing cement content and increasing aggregate content in mix proportion. By using Semi-SCC, number of workers needed for vibrating this concrete is lower than that of workers using normal concrete. Therefore total cost of concrete work in construction project can be reduced. However cement content needed for semi-SCC is still high, thus material cost cannot be significantly reduced. Accordingly, overall of construction budget cannot be obviously reduced.

Generally, unit cost of cement is highest among materials used for concrete. Therefore the method for reducing unit cost of SCC is the reduction in cement content and the increase in aggregate content. The increase in aggregate content apparently affects flowability and self-compactability which is the most important property of SCC. Consequently, flowability and self-compactability have to be improved first, and then aggregate content will be able to be increase results in automatic reduction in cement content. In case of normal concrete, slump which is representing workability of concrete was slightly increased by adding entrained air approximately of 5%. Effect of entrained air on self-compactability of SCC has not been interesting research topic due to the disadvantage of entrained air on concrete that is the reduction in compressive strength which is the main property of concrete. However this research topic has become more interesting because SCC has very high compressive strength, thus the slight reduction in compressive strength is not main problem.

Effect of entrained air on flowability and self-compactability of fresh mortar and concrete are plainly explained as "Ball-bearing effect" that entrained air in concrete matrix trundle fine aggregate particles which is similar to the mechanism of ball bearing in general mechanic tools. The interesting point is that the method to increase effectiveness of ball bearing effect which depends on materials used and mechanism itself. Accordingly, mortar and concrete experiments are important to classify this effect. Self-compacting concrete with entrained air is expected to be alternative material for construction project in near future. The advantages of this concrete are not only in economic phase but also in environmental phase due to the reduction in cement production by mountain explosion.

Chapter 2 Essences of SCC with low cement content by entrained air

Air-Enhanced SCC (AirSCC) is created based on the concept that flowability and self-compactability of fresh concrete can be improved by adding entrained air in mix proportion. By these improvements, aggregate content especially fine aggregate content can be increased, resulted in reduction of cement content and unit cost of SCC respectively. AirSCC is low cost SCC which is expected to be extensively used in near future. Air content (entrained air and entrapped air) for improvement of rheological properties at fresh stage is initially set up as 10%. Compressive strength of concrete reduces approximately 50% by adding entrained air approximately of 10%. Despite the fact that compressive strength of SCC will be reduced 50%, it's still high, compared to compressive strength of normal concrete because the original compressive strength of SCC is very high. Accordingly, compressive strength of AirSCC is sufficient for general construction works. Fine aggregate content of SCC is considered in term of sand to mortar ratio (*s/m*) which represents unit volume of sand per volume of mortar. Sand to mortar ratio (*s/m*) of conventional SCC is recommended approximately of 45% in order to ensure flowability of SCC. To achieve AirSCC with low unit cement content, *s/m* is expected to be increased up to 55%, which results in effective reduction in cement content in mix proportion. Coarse aggregate content is maintained as the same as that of conventional SCC which is approximately of 30% by volume. The last parameter for mix design of SCC is water to cement ratio (*W/C*), *W/C* of conventional SCC is recommended in range of 28-33% in order to prevent segregation of aggregate. Recently, water to cement ratio of SCC can be increased up to 45% without segregation by employing new type of superplasticizer which is blended with viscosity agent from production process. Accordingly the target mix proportion of AirSCC is proposed. Flow behavior of SCC during deformation is considered in the term of shear resistance. Mortar's shear resistance increases due to the increase in normal stress by the approaching of coarse aggregate. Degree of shear resistance depends on sand content in mortar that it will be high due to high amount of sand to mortar ratio (*s/m*) resulting in the limitation of s/m for SCC which is approximately of 45% by volume. To reduce unit cost of SCC, cement content needs to be reduced according to its high unit cost. And sand content is aimed to be increased up to the target value of 55% with flowability enhancement by entrained air of approximately of 10%. Air content of 10% is expected to be sufficient for enhancing flowability due to the increase of *s/m* from 45% to 55% in mix proportion.

Chapter 3 Importance of mortar experiment

To avoid laborious work by mixing various mixes of concrete, mortar experiment was firstly performed. Factors considered in this study were applied to mortar experiment at the beginning in order to initially evaluate flowability of mortar. Once there are significant results are observed, mortar mix proportions will be mixed with real coarse aggregate in order to measure self-compactability and flowability of concrete and to check practicability of mix proportions.

Flowability of mortar is represented as the degree of interaction between model coarse aggregate and mortar ($1\text{-}R_{mb}/R_m$) which can be obtained from standard testing method. Degree of interaction between model coarse aggregate and mortar is represented as $1\text{-}R_{mb}/R_m$ which is obtained from flowability of mortar (R_m) and mortar with model coarse aggregate (R_{mb}). The degree of interaction between coarse aggregate and mortar ($1\text{-}R_{mb}/R_m$) could be used as the preliminary index for evaluating the appropriate mortar for self-compacting concrete by mixing that mortar with real coarse aggregate. The degree of interaction between model coarse aggregate and mortar ($1\text{-}R_{mb}/R_m$) significantly related to the self-compactability of fresh concrete represented by filling height of concrete box test. Although materials used for each mix proportion was different, the relationship between filling height and $1\text{-}R_{mb}/R_m$ is unique. Therefore the index of $1\text{-}R_{mb}/R_m$ is capable to be used to primarily evaluate self-compactability of fresh concrete. Filling height increased gradually due to the decrease of 1-Rmb/R_m from 0.4-0.32. When $1\text{-}R_{mb}/R_m$ reduced to be approximately 0.32, filling height reached the maximum value which is over 300mm. To achieve sufficient self-compactability for SCC that filling height should be higher than 250mm, it could be said that $1\text{-}R_{mb}/R_m$ should be approximately lower than 0.38.

Chapter 4 Factors affecting interaction between model coarse aggregate and mortar

Various materials such as viscosity agent (powder type), new type of superplasticizer and air entraining agent have been studied on improvement of self-compactability of SCC. Self-compactability was slightly increased in mix proportions with moderate *W/C* (*W/C* 32-35%) and low s/m (s/m 45%) by adding viscosity agent in mix. This was not effective materials for improving Self-compactability. New type of superplasticizer was developed and could be used with concrete with *W/C* of 45%. *W/C* could be increased up to 45% and *s/m* could be increased due to flowability improvement by high amount of water. However, self-compactability was not sufficient to achieve desirable SCC. There was significant results on self-compactability improvement by entrained in recently years, thus effect of entrained air on self-compactability improvement was studied.

According to research work in 2014, flowability of self-compacting mortar (SCM) was effectively improved by adding specific type of air entraining agent. The reduction in $1\text{-}R_{mb}/R_m$ means flowability improvement. $1\text{-}R_{mb}/R_m$ reduced by adding entrained air approximately of 8%, which was produced by specific type of air entraining agent combined with new type of superplasticizer (superplasticizer blended with viscosity agent). However negative result on flowability has been found although air content was similar to other mixes. Unfortunately, the stability of entrained air was very low. Air content decreased approximately 50% within 2 hrs which was the main problem for this research. Accordingly, the authors attempted to improve flowability of SCM and SCC by adding entrained air and improve stability of entrained air simultaneously.

Chapter 5 Air-enhanced self-compactability of fresh concrete

New mixing method called "Water dividing mixing method" was introduced in order to increase self-compactability and to prevent air loss during fresh stage. By this method, water was halved into 2 parts and separately mixed with superplasticizer and air entraining agent. After cement and sand were mixed for 30 second, the first half of water with superplasticizer was add and mixed for 1 minute, the 2nd half of water with air entraining agent was added in the end and mixed for 1 minute. To achieve target air content which is approximately of 13%, excessive dosage (over 0.05% of cement weight) of air entraining agent is necessary while 0.005% is sufficient to produce target air content by simple mixing method. Initial air content slightly increased from 13-14% by dosage of air entraining agent from 0.05-0.20%. There was significant result on flowability of mortar by water dividing mixing method. $1\text{-}R_{mb}/R_m$ of mix proportions mixed by water dividing mixing method was apparently lower than that of mix proportions mixed by simple mixing method, compared with the same target air content. This means that flowability of mortar could be improved by new mixing method. Furthermore, $1\text{-}R_{mb}/R_m$ could be reduced more by increasing dosage of air entraining agent up to 0.15%. In addition, the reduction in air content was approximately 2.5% in 2 hrs which was approximately 20% of total air content. Stability of air and flowability of mortar were improved by water dividing mixing method. Accordingly, this method was verified with concrete experiment in order to ensure the practicability concrete industry. In concrete experiment, self-compactability represented by filling height that concrete flow through obstacle. Concrete flowing through obstacle over 250mm can be judged as high self-compactability concrete (SCC). Air content in concrete varied in small range of 9.4-10.4% which was the target value for new type of self-compacting concrete. Compressive strength of concrete decreased approximately 50% by increasing air content approximately of 10%. Therefore compressive strength of new type of SCC will become 30-35 Mpa which is still high comparing to compressive strength of normal concrete. Filling height of concrete apparently increased by water dividing mixing method. By simple mixing method with air content of approximately 10%, filling height was 140 mm whereas it's over 200 mm by water dividing mixing method. Moreover filling height increased from 215-265 mm according to the increase in dosage of air entraining agent from 0.05-0.20%. Self-compacting concrete with air content of approximately 10% has been achieved. This concrete was named as Air-enhanced self-compacting concrete (AirSCC) which is concrete with sufficient self-compactability for casting without vibration and contain air content of approximately 10%. However water dividing mixing and method excessive dosage of AE are necessary for AirSCC. Cement content in AirSCC is approximately 370 kg/m^3 which is approximately 70 kg/m^3 higher than that of normal concrete. Labor cost and unit cost of concrete for concrete work is able to be effectively reduced by using AirSCC. AirSCC is an alternative concrete material for construction project that the budget is the first priority and that project doesn't need high strength concrete.

Chapter 6 Characteristics of bubbles at hardened stage

The mechanism that entrained air enhances flowability of mortar and concrete is Ball bearing effect. Effective entrained air produced by specific type of air entraining agent enhances flowability by trundling sand particles in mortar matrix. According to previous research, the problem of effective entrained air is stability itself. It's necessary to improve both ball bearing effect and stability of air simultaneously. The important point is fundamental properties of effective entrained bubble for improvement of ball bearing effect. Consequently basic characteristics of entrained bubbles will be measured by Linear Traverse Method (LTM) following ASTM C457. Moreover the method to increase stability of air is also presented.

Self-compactability of fresh concrete was effectively improved by entrained air with effective mixing method although air content was similar to that of mix with simple mixing method. This might depends on characteristics of bubbles produced by different mixing method. Accordingly, measurement of diameter and number of bubbles was performed by using Linear Traverse Method in accordance with ASTM 457. There was significant difference in size distribution of bubbles produced by simple and water dividing mixing method. Bubbles with diameter smaller than 0.5 mm were produced approximately of 90% of total air volume by water dividing mixing method with excessive dosage of air entraining agent. Whereas those bubbles were produced approximately 64% by simple mixing method with normal dosage of air entraining agent. Water dividing mixing method needed excessive dosage of air entraining agent to produce air content of approximately 13%. Air content was 7.4% by adding normal dosage of air entraining agent and volume of small bubbles smaller than 0.5 mm was 76%. Normal dosage could not achieve target air content and 90% of volume of small bubbles. According to the results that degree of interaction between model coarse aggregate and mortar ($1-R_{mb}/R_m$) was mitigated by water dividing mixing method, high amount of bubbles smaller than 0.5 mm was suitable for improving self-compactability. To achieve sufficient self-compactability of mortar with s/m of 55%, air content of approximately 13% is necessary and the most important thing is that 90% of total air content should be small bubbles which can be produced by water dividing mixing method with excessive dosage of air entraining agent. It can be said that small bubbles (smaller than 0.5 mm) needed for achieving sufficient self-compactability of mortar was approximately 11.5%.

Chapter 7 Conclusions

Air-enhanced self-compacting concrete (AirSCC) was successfully achieved by introducing water dividing mixing method with excessive dosage of air entraining agent.

However type of air entraining agent used has to be compatible with superplasticizer. These mixing method and dosage of air entraining agent produced high amount of small entrained bubbles especially bubbles of which diameter lower than 0.5 mm. This size of bubbles is effective in mitigation of $1\text{-}R_{mb}/R_m$, resulted in self-compactability improvement of self-compacting concrete. Moreover stability of air is improved simultaneously by new mixing method. Accordingly, fine aggregate content can be increased due to preferable self-compactability. Unit cement content in mix proportion can be automatically reduced according to the increase of fine aggregate and the replacement of air. Finally, unit cost of SCC is effectively reduced due to apparent reduction in cement content. Unit cost of AirSCC with air content of 10% is approximately 28% lower than that of conventional SCC (using unit materials cost in Japan). And it is approximately 27% higher than that of normal concrete. AirSCC is capable to be alternative concrete material that can be used in general construction project.