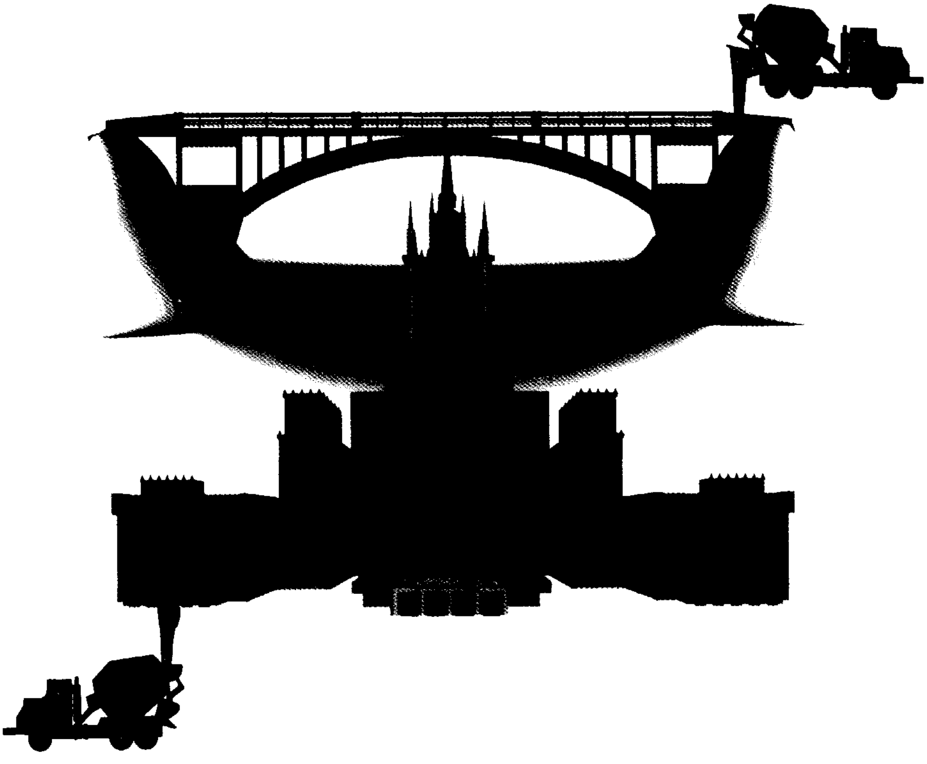
K. Takada

# INFLUENCE OF ADMIXTURES AND MIXING EFFICIENCY ON THE PROPERTIES OF SELF COMPACTING CONCRETE

## The Birth of Self Compacting Concrete in the Netherlands



# Influence of Admixtures and Mixing Efficiency on the Properties of Self Compacting Concrete

# Influence of Admixtures and Mixing Efficiency on the Properties of Self Compacting Concrete

## - The Birth of SCC in the Netherlands -

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.dr.ir. J.T.Fokkema
voorzitter van het College voor Promoties,
in het openbaar te verdedigen

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door

Kazunori TAKADA

Master of Engineering aan de University of Tokyo
geboren te Tokyo, Japan.

*Dit proefschrift is goedgekeurd door de promotor*:
Prof.dr.ir. J.C. Walraven

*Samenstelling promotiecommissie*:

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|---|---|
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| Dr.ir. A. Fraay | Technische Universiteit Delft |

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I came across the technology of self compacting concrete (SCC) in July 1989 when I was an undergraduate student at the Department of Civil Engineering of the University of Tokyo. I joined the first open experiment of "High Performance Concrete" at the campus of the university, and worked in the concrete laboratory just for a number of months. I vibrated the conventional concrete without any clear idea, but it caused segregation and did not succeed to fill the model formwork. On the other hand, "the" concrete surprised me very much because it filled the narrow spaces quite easily without any vibration. Since then, 15 years ago, I have always wanted to be a witness of how the innovative concrete changes the conservative construction industry, and as a result, I am now defending my PhD-Thesis in Delft in the Netherlands, far away from the place where I firstly met SCC.

Prof. K. Maekawa (University of Tokyo) is one of the inventors of "High Performance Concrete" and he advised me to go to Delft. Prof. K. Ozawa (University of Tokyo) is another founder of SCC, and he supervised my master study and gave me a lot of instructions during my stay in Delft, too. I thank both of them for letting me stand at the starting line of this Ph.D. study. Of course, I would like to express my gratitude and respect to Prof. H. Okamura (the president of Kochi University of Technology, professor emeritus of the University of Tokyo) who showed me the dream of "High Performance Concrete" and the right attitude as a scientist and a researcher.

This thesis reports the discussion based on the result of experiments carried out during my stay in the Stevin Laboratory of the Faculty of Civil Engineering of Delft University of Technology in the period 1996-1998. Prof. K. van Breugel, who was my first teacher in Delft, gave me very valuable knowledge on autogenous shrinkage of high strength concrete that was helpful for my research work in Kajima Technical Research Institute (KaTRI) afterwards. The technical staff members and Ph.D. students of the Stevin Laboratory accepted me as a colleague for the two years. I thank them for their kind hospitality. Especially, Mr. R. van der Baars and Ms. G. I. Pelova helped me with the experiments on mortar and paste, and by their kind cooperation I was provided with many variable test results. I furthermore thank Mr. T. Steijn, who spent a lot of time to harmonize the drawings in this thesis, and Mrs. L. Ton for preparing the final text.

All the experiments on concrete including the development of the Dutch prototype of SCC were supported by the great cooperation and research spirit of Mr. M. Langbroek, Mr. A. van der Ham and Mr. G. van den Berg of Cementbouw B.V. Furthermore SCC was spread on the Dutch construction market by them after I left the Netherlands, so that the work had it's impact on the industry. I respect their effort made for the promotion of SCC and I believe that our friendship will never break in future.

The tests on cement paste composing the main part of this thesis were carried out at the Research Institute of the Cement Industry of German Cement Works Association in Düsseldorf. Their viscometer and the skillful help of Mrs. I. Leiti made the desirable experimental data available during my short stay of half a month in Düsseldorf. I am grateful for the kind cooperation with and support by Prof.Dr.-Ing. G. Thielen, Dr.-Ing. H. Grube and Dr.-Ing. G. Spanka, who offered me the free use of their facilities and technical support.

This research project was financially supported by STW (Dutch Science Foundation) and SPOB (Dutch organization for research and development of concrete products). Furthermore some materials and data were offered by the Vliegasunie (Dutch Fly Ash Corporation). They are gratefully acknowledged.

Fundamentally, I am a civil engineer and my knowledge on the chemistry of superplasticizers is not my basic field of expertise. Therefore, the considerations in the research are mostly not beyond the visible phenomena. However, if the quality of the consideration was improved, it is by virtue of Mr. H. Yamamina, Dr. A. Ota and Dr. T. Sugamata (NMB, Masterbuilders Technology Japan) who gave me a lot of suggestions on the additive chemistry. The samples of Japanese superplasticizers offered by them were very helpful in order to evaluate the European products in comparison.

The discussions through e-mail with Dr. Ouchi (Kochi University of Technology), who was a PhD. student and involved in the research on SCC at the University of Tokyo when I was in Delft, raised the level of the methods and considerations of this study. I thank him very much.

The employees of Kajima Europe B.V. helped my Dutch life in various aspects. Many thanks also for the superiors and colleagues of KaTRI, because they helped me to realize my study in the Netherlands, facilitated the transportation of the test equipment and gave me many advices on writing the thesis. Moreover the superiors and colleagues of the Ken-o-do Oido construction site office and Futatsuduka waste disposal site construction office approved me to work for writing my thesis "after 20:00 hrs. in the evening" when I was occupied at the construction site management work. All of them are very much acknowledged. And of course, the way of this 8-years Ph.D. project cannot be completed without the help of my wife and family. I like to say "Thank you".

The meeting with Prof. Walraven, who is the promoter of this thesis and supervisor of the study, has become a quite valuable aspect of my life. His identity as a researcher, his skill of speech with humor and wit, and his personality, I respect all of them. I am happy to get acquainted with such a superior mentor. Actually, I sometimes felt the difficulty of communication with him through a long distance during the period of his president-ship of *fib* because of the busy position. However, he encouraged me at times and led me to the goal. I appreciate him very much. Furthermore, I must thank Prof. H. W. Bennenk (emeritus professor of Eindhoven University of Technology, advisor of BELTON). He gave me a lot of valuable comments in the writing phase of this project.

Finally, I would like to mention my appreciation for the late Dr. Y. Nojiri (a former vice president of Kajima Corporation and a director of KaTRI). He kindly made an effort to send me to the Netherlands especially for the procedures in the firm. Herewith I would like to pray for the repose of his soul again, and would like to report to him the finalization of my Ph.D. program.

# 謝辞

著者が自己充てんコンクリート（SCC）に出会ったのは1989年7月，東京大学工学部土木工学科第4学年に在学中のことでした。その年の春に卒論生としてコンクリート研究室に配属となってまもなく，当時“ハイパフォーマンスコンクリート”と名づけられたそのコンクリートの初めての公開実験に参加しました。訳も分からずバイブレータを握り，比較対照であった普通コンクリートを盛んに締め固めましたが，材料分離を起こすばかりで用意されたモデル型枠は充てんされませんでした。一方でそのコンクリートが一切バイブレータをかけずとも，難なく狭隘な隙間を埋め尽くしていく様にただ驚かされました。以来15年間，“この革新的なコンクリートがどのように建設の世界を変えていくのかをこの目で見てみたい”という気持ちを持ち続けた結果，今日，母校から遠くはなれたオランダ・Delftの地で学位を頂くこととなりました。

“ハイパフォーマンスコンクリート”の発明者の一人であり，著者の留学先として「Delftへ行け」と背中を押してくださった前川宏一博士（東京大学工学系研究科教授），同じく発明者の一人で，著者の修士論文をご指導いただき，留学中も公私にわたる助言を頂いた小澤一雅博士（東京大学新領域創成研究科助教授）には，今日ここへたどり着くためのスタートラインを与えてくださったことに深く感謝いたします。そして，“ハイパフォーマンスコンクリート”への夢と研究者としての基本姿勢を教えてくださった岡村甫博士（高知工科大学学長，元東京大学工学系研究科教授）を心より尊敬申し上げます。

本研究は，1996年9月～1998年8月の2年間，オランダ・Delft工科大学土木工学部のStevin Laboratoryに客員研究員として滞在した間に行った実験の結果を取りまとめたものです。初めに指導いただいた，K. van Breugel教授には，高強度コンクリートの自己収縮に関して，その後の鹿島技術研究所での研究開発業務に大いに役立つ知見を与えていただきました。また2年間の滞在中，仲間として接してくれたStevin Laboratoryの技術スタッフとPh.D.コースの学生たちに厚くお礼申し上げます。特に，モルタル・ペーストの実験を手伝ってくれたMr. R. van der BaarsとMs. G. I. Perovaの協力は，著者に多くの有用な実験データを与えてくれました。また，Mr. T. Steijnは本論文中の図・表の調整・調和に多くの時間を割いていただきました。有難うございました。

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本論文のメイン・パートを構成するセメントペーストの実験は，Düsseldorf にあるドイツセメント協会・セメント産業研究所の協力と施設をお借りして行いました。Delft 工科大には無かったモルタル・ペースト用の回転粘度計と Ms. I. Leiti の手際のよいアシストが，半月ほどの短い滞在期間に思い通りのデータ採取を可能としてくれました。無償で施設と技術補助をご提供くださった，Prof. G. Tielen，Dr. H. Grube，Dr. G. Spanka のご協力に感謝いたします。

なお，本研究は STW (Dutch Science Foundation)および SPOB (Dutch organization for research and development of concrete products)の研究助成金を活用して実施しました。また，Vliegasunie (Dutch Fly Ash Corporation)には材料と物性データの提供を頂きました。

本研究を行うにあたり，“土木屋”の著者には高性能減水剤に関する化学的な知識が乏しく，考察は目に見える現象からの推測の域を出ていないのが正直なところですが，その推測の程度がやや高められたとすれば，それは山宮浩信様（ポゾリス物産㈱），太田晃博士，菅俣匠博士（㈱エヌエムビー）にご示唆頂いた知見のおかげです。さらに日本製の高性能減水剤サンプルをオランダまでお送りいただき，当時の欧州製品との比較を行う上でも大変役立たせて頂きました。また，著者の留学中，母校の博士課程で SCC の研究に没頭しておられた大内正博博士（高知工科大学助教授）との e-mail を介しての議論は，本研究の手法と考察に厚みを与えてくれました。感謝いたします。

オランダでの生活を様々な面で支えてくださった Kajima Europe B.V.の社員の皆様，留学実現のバックアップ，現地への実験器具の輸送，帰国後の論文作成への助言など少なからずお世話になった鹿島技術研究所の上司・同僚の皆様，そして現場勤務中も“夜８時以降”の論文作成を黙認してくださった東京支店西部土木営業所・圏央道大井戸工事事務所および二ツ塚廃棄物処分場建設工事事務所の皆様には，心よりの感謝とご報告を申し上げます。そして渡蘭以来今日までの８年間，見守り続けてくれた妻・家族の協力無くして，ここにたどり着くことは不可能でした。ありがとう。

本論文のプロモーターであり，研究のスーパーバイザーであった J. C. Walraven 教授と出会えたことは，著者の人生にとって大きな財産となりました。研究者としての志，ユーモアとウィットに富んだ語り口，そして人格，どれをとっても尊敬に値するすばらしい師と出会えたことを心より幸せに思います。fib 会長という重職に就かれた間は，遠くはなれた日本からのコミュニケーションの難しさを感じたこともありましたが，折に触れ励ましの言葉をかけていただいたことで，何とかここに論文の完成を見ることができました。有難うございました。また，Walraven 先生と共に本論文の執筆段階でご指導を頂いた，H. W. Bennenk・Eindhoven 工科大名誉教授にも感謝の意を表します。

最後に，著者のオランダ留学の実現にご尽力をいただき，大変お世話になりました，故・野尻陽一博士（元鹿島建設㈱副社長・技術研究所長）に学位取得のご報告を申し上げ，ここに改めて博士のご冥福をお祈りする次第です。

# SUMMARY

SCC, Self-Compacting Concrete, was initially developed in Japan in 1988 at the University of Tokyo by Prof. *Okamura* and his colleagues. SCC has been applied in many actual construction projects since the early 1990's. However, the SCC technology had not been spread on a world-wide scale when the author started his guest researcher-ship at Delft University of Technology in 1996. SCC was a topic of interest in the Dutch concrete industry.

In order to fulfill the interest of the Dutch concrete industry, the first stage of the project aimed at verifying the producibility of SCC in a laboratory of a Dutch ready-mixed concrete plant applying Dutch local materials. Within the scope of this work, a recommendation for a Dutch prototype SCC mixture and a quality control method was aimed at.

After the development of the prototype, the research focused on the application of very fine mineral admixtures, so-called "microfillers" as a material for SCC. An investigation of the effect of coal gasification fly ash (CGFA), which is a very fine and round-shaped fly ash which newly appeared on the Dutch market, was carried out in comparison with the performance of other microfillers, like silica fume and micronized fly ash.

After the previously described two-stage contribution to the Dutch concrete industry (research phase-I), the research project shifted to the influence of mixing and chemical admixtures on the behavior of SCC (research phase-II). The influence of mixing on the mixture proportioning of SCC is still unknown. Therefore, an investigation of this subject could provide the necessary information for further rationalization of the mixture design procedure for SCC. This is the main purpose of this project. Within this scope, the influence of chemical admixtures, the type of superplasticizer and the use of a viscosity modifying admixture, were also studied because the mixing efficiency is clearly affected by the type of chemical admixtures used.

In Chapter 1, the scope and the aim of the research project are outlined. It includes the research strategy and the structure of the report as well. Chapter 2 deals with a literature survey.

The development of SCC using Dutch local materials applying the Japanese mixture design method is reported, and the result of the trial is described in detail in Chapter 3. A recommendation for a Dutch prototype SCC mixture and quality control values was developed, as listed in the following:

Powder composition : BSC-A 60%+FA 40% in volume

Superplasticizer : SP-A&B combining ratio 1:2.5

Fine aggregate : normal river sand, $S_c/M=40\%$

Coarse aggregate : normal river gravel, maximum size=16mm, $G/G_{lim}=55\text{-}58\%$

Welan Gum : 0.05% to water weight (not essential)

Quality control : Slump flow=650±50mm, V funnel time=10±2 -13±2 sec. according to $G/G_{lim}$

Example of SCC NL-prototype

| | unit quantity (kg/m$^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | W | BSC-A | FA | S | G | SP-A | SP-B | Welan gum |
| NL-prototype | 165 | 341 | 180 | 642 | 949 | 0.84* | 2.10* | 0.082 |

*: volume of SP is included in W

In Chapter 4, three microfillers, silica fume, coal gasification fly ash and micronized fly ash are investigated as a material for SCC with advantageous performance. The coal gasification fly ash (CGFA) recently appeared as a secondary material for which it is tried to find a satisfactory usage both from an economical and ecological point of view. In this chapter, the competence of CGFA as a material for concrete is studied in detail and the role of microfillers in concrete mixtures is discussed.

As a result of the study, it was recognized that CGFA was a very useful material for high-strength SCC for the following reasons:

- CGFA can substantially reduce the viscosity of the fresh concrete as well as silica fume, although CGFA itself does not have the ability to increase the strength of a hardened cementitious composite like silica fume does. In other words, a small dosage of CGFA improves the workability of fresh concrete with a very low water-binder ratio.
- The application of CGFA does not have a side effect spoiling the deformability of a fresh concrete mixture (so that a higher amount of superplasticizer is required to obtain a proper deformability) like silica fume does.

In Chapter 5, the influence of the mixing efficiency on realizing defined properties of fresh SCC is investigated. A number of concrete mixing tests is described with varying mixing procedures and types of mixers and it is claimed that the necessary mixture proportion for obtaining an SCC with specified characteristics depends on the mixing efficiency. General tendencies are described as follows:

- In order to control the slump flow and the V funnel time at the target values,
  - A smaller water-powder ratio requires a larger mixing energy.
  - A larger dosage of superplasticizer (polycarboxilic ether based) requires a larger mixing energy.

Furthermore, a hypothesis for the effect of mixing on the properties of fresh SCC is given to explain what happens in concrete during mixing. The three hypotheses are:

- Mixing effect 1: Effect on the dispersion of powder particles
- Mixing effect 2: Effect on processing powder particles' surfaces
- Mixing effect 3: Effect on air bubble generation in the paste phase of fresh concrete

In Chapter 6, the verification of the hypothesis on the mixing efficiency formulated in Chapter 5 is given. A very intensive and well-controlled testing program on flowable cement pastes with dosed superplasticizer, and in some cases a viscosity modifying admixture, is performed in order to clarify the influence of mixing on the properties of the paste phase of fresh concrete, because it is logical to assume that especially the properties of the paste are influenced by the mixing, whereas the aggregate can be considered to be indifferent. On the basis of the results of the experiments, the influence of the mixing efficiency on the properties of the fresh cement paste is investigated in detail and the interaction between the effects of chemical admixtures and mixing intensity is clarified. The conclusions obtained are as follows:

- The fresh properties of cement paste are substantially influenced by the mixing. Conversely, cement pastes with different proportions can show the same rheological characteristics by controlling the mixing procedures.
- "Mixing effect 1" is applicable to explain the behavior of cement paste mixtures with both types of superplasticizer, the polycarboxylic ether type and the naphthalene sulfonate type.
- "Mixing effect 2" is not applicable to explain the behavior of cement paste mixtures. On the basis of the comparison between the results of the paste tests and the mortar-concrete tests, it can be concluded that the action of the aggregate grains in mortar and concrete plays a role in causing the effect.
- "Mixing effect 3" is clearly applicable to explain the behavior of the cement paste mixtures with a non-AE type of superplasticizer. However, it is not applicable to the mixtures with a superplasticizer which has a chemical air-entraining effect.
- A polycarboxylic ether based superplasticizer is considered to be helped by the mixing energy to disperse the powder particles. As a consequence, more energetic mixing makes the cement paste mixtures less viscous. Moreover a larger dosage tends to result in a less viscous mixture.

- A naphthalene sulfonate based superplasticizer disperses the powder particles spontaneously by its electrostatic repulsion effect, so the effectiveness of mixing is smaller than for a polycarboxylic ether based superplasticizer. Furthermore the influence of dosage on the viscosity of the mixture is small.
- When using a polycarboxylic ether based superplasticizer, the dosage of Welan Gum increases the degree of the hypothesized "Mixing Effect 1". However, this effect of Welan Gum does not happen when it is combined with a naphthalene sulfonate based superplasticizer.

Finally, the results and conclusions of this research project are summarized and a direction for future work on the popularization of SCC is given in Chapter 7. Especially, a suggestion is given for an ideal role and function of superplasticizers for SCC, based on the original concept of SCC and the knowledge obtained in this research project.

# SAMENVATTING

ZVB, Zelf Verdichtend Beton, werd oorspronkelijk in 1988 in Japan aan de Universiteit van Tokyo door Professor Okamura en zijn collega's ontwikkeld. Sinds 1990 is ZVB toegepast in een aanzienlijk aantal constructies. Niettemin was de technologie van ZVB buiten Japan nauwelijks ontwikkeld toen de auteur zijn werk als gastonderzoeker aan de Technische Universiteit Delft in 1996 begon. ZVB bleek een onderwerp te zijn waarin de Nederlandse betonindustrie geïnteresseerd was.

Om aan de interesse van de Nederlandse betonindustrie tegemoet te komen werd het eerste deel van het onderzoeksproject gewijd aan de vraag of ZVB in het laboratorium van een Nederlands Betonbedrijf kon worden geproduceerd met lokaal aanwezige, Nederlandse materialen. In het kader van dit onderzoek werd een aanbeveling gedaan voor een Nederlands prototype ZVB en werd een controlemethode vastgesteld.

Na de ontwikkeling van het prototype-mengsel werd het onderzoek toegesneden op de mogelijke toepassing van fijne minerale hulpstoffen, de zogenaamde "micro-vulstoffen", in ZVB. Een onderzoek werd uitgevoerd naar de werking van kolenvergassingsvliegas (KVV), een erg fijne and rondkorrelige vliegas, die juist op de Nederlandse markt was verschenen. De werking van dit materiaal werd vergeleken met het gedrag van andere microvulstoffen, als silicafume en gemicroniseerde vliegas.

Na de hiervoor beschreven tweeledige bijdrage aan de Nederlandse betonindustrie (onderzoeksfase I), werd het onderzoek verschoven naar de invloed van het mengen en de werking van chemische hulpstoffen op het gedrag van ZVB (onderzoeksfase II). De invloed van het mengen op de voor ZVB vereiste mengselsamenstelling was nog niet bekend. Daarom kon een onderzoek op dit gebied de noodzakelijke informatie verschaffen voor verdere rationalisering van het mengselontwerp van ZVB. Dit was het hoofddoel van het project. Binnen dit kader werd de invloed van chemische hulpstoffen, het type superplastificeerder en het gebruik van een viscositeits-regelende hulpstof onderzocht, omdat de effectiviteit van het mengen duidelijk wordt beïnvloed door deze stoffen.

In hoofdstuk 1 worden het kader en het doel van het onderzoeksproject toegelicht. Hierbij wordt ook de strategie van het onderzoek en de structuur van het rapport behandeld. Hoofdstuk 2 geeft een literatuuroverzicht.

De ontwikkeling van ZVB met lokaal in Nederland beschikbare materialen, met toepassing van de Japanse principes voor de mengselsamenstelling, wordt in detail beschreven in hoofdstuk 3. In de volgende tabel wordt, op grond van dit onderzoek, een aanbeveling gegeven voor een Nederlands prototype ZVB:

Bindmiddelsamenstelling: 60 Vol.-% Hoogovencement A en 40 Vol.-% Vliegas
Superplastificeerder: SP-A&B in verhouding 1:2,5
Fijne toeslag: normaal rivierzand, $S_c/M = 40\%$
Grove toeslag: normaal riviergrind, $D_{max} = 16$ mm, $G/G_{lim} = 55\text{-}58\%$
Welan gum: 0,05% van het watergewicht (niet essentieel)
Kwaliteitskontrolle: Vloeimaat = 650 ± 50 mm, V-trechter doorstroomtijd = 10 ± 2 tot 13± 2 sec, afhankelijk van $G/G_{lim}$

Tabel: Prototype ZVB voor Nederland

| Water Kg/m$^3$ | HOC-A Kg/m$^3$ | Vliegas Kg/m$^3$ | Zand Kg/m$^3$ | Grind Kg/m$^3$ | SP-A Kg/m$^3$ | SP-B Kg/m$^3$ | Welan gum Kg/m$^3$ |
|---|---|---|---|---|---|---|---|
| 165 | 341 | 180 | 642 | 949 | 0,84*) | 2,10*) | 0,082 |

*) Volume SP opgenomen in watergehalte

In hoofdstuk 4 worden de drie microvulstoffen silicafume, kolenvergassingsvliegas en gemicroniseerde vliegas onderzocht op hun geschiktheid voor ZVB. De kolenvergassingsvliegas kwam kort voor het onderzoek op de markt als een reststof, waarvoor een economisch en ecologisch verantwoorde toepassing werd gezocht . In dit hoofdstuk wordt de geschiktheid van kolenvergassingsvliegas in detail bestudeerd en wordt de rol van microvulstoffen in betonmengsels besproken.

Als resultaat van de studie bleek dat kolenvergassingsvliegas een zeer geschikt materiaal is voor de toepassing in hoge-sterkte ZVB, en wel om de volgende redenen:

- Kolenvergassingsvliegas kan de viscositeit van vers beton, net als silicafume, significant verlagen, hoewel kolenvergassingsvliegas niet hetzelfde sterkte-verhogende effect heeft. Met andere woorden, een kleine dosering KVV verbetert de verwerkbaarheid van vers beton met een lage water-bindmiddel factor.
- De toepassing van KVV vertoont geen bijwerking met betrekking tot het verlagen van de vervormbaarheid (vloeimaat) van verse betonspecie, wat wel bij silicafume het geval is.

In hoofdstuk 5 wordt de invloed van de mengeffectiviteit op de realisatie van verse zelfverdichtende betonspecie behandeld. Er wordt een aantal tests beschreven waarbij het beton volgens verschillende procedures wordt gemengd. Vastgesteld wordt dat de mengselsamenstelling, nodig om tot specifieke eigenschappen van het beton te komen, van de mengeffectiviteit afhangt. Om de vloeimaat en trechterdoorlooptijd op de gewenste waarden te houden gelden de volgende algemene tendensen:

- een grotere mengenergie vereist een kleinere water–bindmiddel verhouding
- een grotere mengenergie vereist een hogere dosering (polycarboxil-ether gebaseerde) superplastificeerder. Eerder werden een aantal hypotheses opgesteld die het effect van de mengenergie op de eigenschappen van verse ZVB-specie verklaren:
- Mengeffekt 1: effekt op de verspreiding van de bindmiddeldeeltjes
- Mengeffekt 2: effekt op de modificatie van de oppervlakte van de bindmiddeldeeltjes
- Mengeffekt 3: effekt op luchtbelvorming in de pastacomponent in de verse betonspecie

In hoofdstuk 6 wordt de verificatie van de hypothesen ten aanzien van de mengeffectiviteit, als geformuleerd in hoofdstuk 5, gegeven. Een zeer intensief en goed gecontroleerd proevenprogramma werd uitgevoerd op vloeibare cementpasta met variërende doseringen superplastificeerder, en soms met een viscositeits-regulerende hulpstof. Hierbij werd de invloed van de mengmethode op de eigenschappen van de pasta-component in verse betonspecie onderzocht. Dit ligt voor de hand, omdat in verse betonspecie vooral de pasta-component wordt beïnvloed, terwijl de toeslag indifferent is. Op basis van de resultaten van de experimenten is de invloed van de mengeffectiviteit op de eigenschappen van de verse pasta in detail onderzocht en wordt de wisselwerking tussen de chemische hulpstoffen en de wijze van mengen verklaard.

De volgende conclusies werden getrokken:

- De eigenschappen van een verse cementpasta worden sterk beïnvloed door de wijze van mengen. Het is zelfs mogelijk dat cementpasta's met verschillende samenstellingen door de keuze van de mengmethode uiteindelijk dezelfde eigenschappen krijgen.
- "Mengeffect 1" is van toepassing om het gedrag van cementpasta mengsels met beide typen gebruikte superplastificeerder, het polycarboxiltype en het naftaleen-sulfonaat type, te verklaren.
- "Mengeffect 2" is niet van toepassing om het gedrag van cementpasta mengsels te verklaren. Op basis van de vergelijking tussen de resultaten van de tests op cementpasta en op betonspecie kan worden geconcludeerd dat de werking van de toeslagkorrels in mortel en beton een rol speelt om het effect te verwezenlijken.

- "Mengeffect 3" is duidelijk van toepassing om het gedrag van cementpasta mengsels met een niet luchtbelvormende superplastificeerder te verklaren. Het is daarentegen niet toepasbaar op mengsels met luchtbelvormende superplastificeerders.
- De werking van een superplastificeerder op basis van polycarboxilether, ten aanzien van het dispergeren van de bindmiddeldeeltjes, wordt ondersteund door de mengenergie. Als gevolg daarvan maakt intensiever mengen de cementpasta mengsels minder viskeus. Verder leidt een hogere dosis suprplastificeerder tot een minder viskeus mengsel.
- Een superplastificeerder op naftaleen sulfonaat basis dispergeert de poederdeeltjes spontaan door haar electrostatische afstotingseffekt. Daardoor is het effect van intensiever mengen kleiner dan bij het gebruik van een polycarboxil-ether superplastificeerder. Verder is de invloed van een hogere dosering superplastificeerder op de viscositeit klein.
- Wanneer een superplastificeerder op basis van polycarboxil-ether wordt gebruikt, vergroot de toevoeging van Welan gum de werking van "Mengeffect 1". Dit effect van Welan gum treedt echter niet op wanneer het gecombineerd wordt met een superplastificeerder op basis van naftaleensulfonaat.

Ten slotte worden in hoofdstuk 7 de resultaten en de conclusies van het gehele onderzoeksproject samengevat en wordt een richting aangegeven om ZVB in de toekomst in bredere zin toepasbaar te maken. In het bijzonder wordt een suggestie gedaan voor een ideale rol en functie van superplastificeerders in ZVB gebaseerd op het oorspronkelijke concept van ZVB en de kennis die in dit project werd opgedaan.

# 論文要旨

自己充てんコンクリート（SCC）は，1988年に東京大学の岡村甫教授（現・高知工科大学長）グループによって発明された，日本発のコンクリート技術である。1990年代初頭より実構造物への適用が始まり，著者が客員研究員としてDelft工科大へ渡った1996年には，日本国内においてはすでに実用技術として一定のレベルに達していた。しかし世界的には，ほとんどの国々でその実態も十分に知られておらず，ごく一部の国で研究が始まった段階であった。オランダのコンクリート業界でも，一部でSCCの開発が試みられてはいたが，興味が先行しているという状況であった。

そのような背景のもと，オランダ・レディーミクストコンクリート業界の強い要請により，本研究の第一ステージは，現地の市場で入手可能な材料を用い，オランダの生コンプラントの試験室の設備を使って製造可能なSCCの配合を見出すことに設定された。すなわち，“ダッチ・プロトタイプ”の配合，品質管理試験方法およびその基準値の範囲を示すことが目的とされた。

プロトタイプ配合の開発に続き，セメントよりも細かい超微粉末材料，いわゆる“マイクロフィラー”のSCCへの適用性を評価する研究を，やはり当地の無機混和材メーカの依頼を受けて行うこととなった。当時，オランダ市場に登場したばかりであった，非常に細かい球状粒子から成る“石炭ガス化フライアッシュ”の適用性を，シリカフュームおよび微粉砕フライアッシュと比較することにより評価することを試みた。

オランダ・コンクリート産業界から委託されたこれら２種類の研究（フェーズI）の後，課題はSCCの性状に及ぼす練混ぜおよび化学混和剤とその相互作用に関する研究（フェーズII）へと移った。練混ぜがSCCの配合設計にどのような影響を及ぼしているかについては，未だ定量的な考察と理論構築はなされていない。したがって，この課題に取り組むことにより，SCCの配合設計の合理化・適正化に必要な情報を世の中に提供することができると考え，本研究の主たる目的とした。また，使用する高性能減水剤の種類，および特殊増粘剤（ウエランガム）の使用の有無についても検討のパラメータに加えた。なぜなら，練混ぜがSCCのフレッシュ性状に及ぼす影響は，使用する化学混和剤のタイプによって度合いが異なることを，以前から感覚的に認識していたからである。

第１章では本研究の範囲と目的，研究の方法および論文の構成などについて概説した。関連する既往の研究については第２章にまとめた。

第３章では，日本の配合設計理論を応用し，オランダの材料を用いた SCC “ダッチ・プロトタイプ” の開発について，その詳細をレポートした。 以下に本研究によって得られた配合パラメータの推奨値と品質管理基準を示す。

粉体構成 ：BSC-A 60%+FA 40% （容積比）

高性能減水剤 ：SP-AとBを混合比1:2.5で使用

細骨材（０～４mm） ：川砂， $S_c/M$=40%

粗骨材（４～１６mm）:川砂利， $G/G_{lim}$=55-58%

ウエランガム ：単位水量の0.05重量% (必要に応じて使用)

品質管理 ：スランプフロー：650±50mm, Vロート=10±2～13±2 秒.（$G/G_{lim}$による）

**SCC NL-prototype の配合例**

| | unit quantity (kg/m$^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **W** | **BSC-A** | **FA** | **S** | **G** | **SP-A** | **SP-B** | **Welan gum** |
| **NL-prototype** | **165** | **341** | **180** | **642** | **949** | **(0.84)** | **(2.10)** | **0.082** |

( ): volume of SP is included in W

第４章では，さらなる付加価値として“高強度”を取り上げ，高強度 SCC の材料として３種類の超微粉末材料（シリカフューム，石炭ガス化フライアッシュ，微粉砕フライアッシュ）の適用性を検討した。“石炭ガス化フライアッシュ”（CGFA）は近年オランダで実用化されている石炭ガス化発電から排出される材料で，経済性と環境の観点からその有効な再利用法が必要とされている。本章では，CGFA のコンクリート用材料としての適正を詳細に評価すると共に，コンクリートの挙動に及ぼす超微粉末材料の影響と役割について考察した。

検討の結果, CGFA はシリカフュームのようにそれ自体が硬化体の強度を増進させる効果は無いものの，シリカフュームと同様にフレッシュコンクリートの粘性を著しく低減させる効果があることが分かった。すなわち，少量の添加によって低水結合材比フレッシュコンクリートの施工性を改善することができる。さらに，シリカフュームのように添加量に伴ってフレッシュコンクリートの変形性が損なわれる（変形性を保持するために高性能減水剤の使用量が増加する）という副作用がないため，高強度 SCC の材料として高い適用性を有する材料であることが確認された。

第５章では，規定した SCC のフレッシュ性状を実現する上で，練混ぜ効率の違いが如何に配合設計に影響を及ぼすか，について実験的な研究を行った。練混ぜの手順やミキサー

の種類を変化させた室内練混ぜ試験を数多く実施した結果，目標とする性状を示すSCCを得るためには，練混ぜ方法に応じて異なる配合を設計する必要があることが明らかとなり，その一般的な傾向について考察を行った。ここで明らかとなった練混ぜの定性的な影響は以下のとおりである。

- スランプフロー，Vロートをある目標値にコントロールするためには，
  - □ 練混ぜエネルギーが大きいほど，水粉体容積比を小さくする必要がある。
  - □ 練混ぜエネルギーが大きいほど，高性能減水剤（ポリカルボン酸系）添加率を大きくする必要がある。

さらに，SCCのフレッシュ性状に及ぼす練混ぜの影響について微視的な仮説を提案し，フレッシュコンクリートの練混ぜ中に起こっている現象の説明を試みた。以下に提案した練混ぜ効果の３つの仮説を示す。

- 練混ぜ効果１：粉体粒子の分散効果
- 練混ぜ効果２：粉体粒子表面の改質・加工効果
- 練混ぜ効果３：微細空気泡の導入効果

第６章では，第５章で提案した練混ぜに関する仮説の検証を試みた。フレッシュコンクリートのペースト層に及ぼされる練混ぜの影響を明らかにするため，高性能減水剤を添加したセメントペーストを対象に，練混ぜ条件を厳しく制御した集中的な練混ぜ実験プログラムを実施した。練混ぜによってコンクリート中の骨材が変質するとは考えにくいため，主としてペーストの性質が練混ぜによって変化すると考えたからである。なお，いくつかのケースでは特殊増粘剤（ウエランガム）を併用した。

実験結果から，化学混和剤との相互作用も考慮したうえで，セメントペーストのフレッシュ性状に及ぼす練混ぜの効果について以下の結論を得た。

- セメントペーストのフレッシュ性状は，練混ぜ方法の影響を大きく受ける。逆に，異なる配合のセメントペーストであっても，練混ぜをコントロールすることでレオロジー特性をコントロールすることが可能である。
- “練混ぜ効果１”は，ポリカルボン酸系高性能減水剤を用いたセメントペースト，ナフタレン系高性能減水剤を用いたセメントペーストともに，その効果が認められた。
- “練混ぜ効果２”は，セメントペーストの実験ではその効果は確認されなかった。モルタル・コンクリート実験との対比により，「骨材」が存在する系において発揮される効果であることが分かった。
- “練混ぜ効果３”は，空気連行剤を含まない高性能減水剤を使用した場合には，明確に発揮されることが分かった。一方，高性能AE減水剤を使用したセメントペーストでは練混ぜにより逆に空気量は減少する場合がある。
- ポリカルボン酸系高性能減水剤は，練混ぜのエネルギーに助けられながらセメント粒子を分散させると考察され，練混ぜエネルギーの大小でセメントペーストの粘性が大きく変

化する。また添加率を増すことによって，粘性を低下させる傾向がある。

- ナフタレン系高性能減水剤は，電気的反発力によって自らセメント粒子を分散させるため，練混ぜによる影響はポリカルボン酸系に比べて小さく，添加率による粘性への影響も小さい。
- ウエランガムをポリカルボン酸系高性能減水剤と併用すると，上述の練混ぜによる粘性の変化がさらに大きくなる傾向がある。一方，ナフタレン系高性能減水剤を使用したセメントペーストでは，ウエランガムの添加によって練混ぜの影響が増幅されることはなかった。

最後に，第 7 章では本研究で得られた実験結果および結論を総括し，自己充填コンクリートの発展・普及に向けた技術的課題を論じた。特に，SCC にとっての高性能減水剤のあるべき姿について，SCC 本来の開発コンセプトと本研究から得られた知見をもとに，その方向性を提言した。

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# CHAPTER 1
# INTRODUCTION

## 1.1 GENERAL SCOPE OF THE PROJECT

Concrete was one of the most essential structural materials in the last century and will be so in this century as well. Concrete structures both in civil engineering and building engineering must be durable for their life time. In order to be durable for a long life time, concrete structures should be designed and constructed properly and initial defects must be avoided as much as possible. However, concrete structures gradually become more and more complicated and higher demands are imposed on the quality of their execution. Finally, it is also required that the construction industry should be more environmentally friendly and the working conditions should be improved. This is now a global trend in the construction industry. Self-Compacting Concrete may become a revolution and a solution considering the aspects mentioned before.

In the period 1990-1995 it was tried several times to produce self-compacting concrete in the Netherlands [1]. The mixture composition was developed on the basis of trial and error. The experience was that producing self-compacting concrete was basically possible, but there was always a considerable sensitivity to small variations in the mixture composition and in the characteristics of the constituent materials. Slight variations in moisture content, for instance, resulted whether in sticky behavior or in segregation. A slight over-dosage of the admixture could result in blockage of the pumps.

Intensive control and supervision was necessary to assure the appropriateness of the self-compacting mixtures. A number of pilot projects were carried out [2]. However, due to lack of confidence caused by the uncertainties in the mixture composition and their possible consequences for the construction, the state of general acceptance was then not yet reached.

SCC, Self-Compacting Concrete, was initially developed in Japan in 1988 at the University of Tokyo by Prof. *Okamura* and his colleagues [3][4], and was made freely available to the industry in 1989. Since then, SCC has attracted a great deal of Japanese concrete researchers' and engineers' attention and has been applied in many actual construction projects since the early 1990's. However, the SCC technology, developed and matured in Japan, had not been spread world-widely when the author started his guest researcher-ship at Delft University of Technology in 1996.

The author graduated at the University of Tokyo and completed his master's thesis on the mix design of SCC [5] in 1992 under supervision of Prof. *Okamura* and Dr. *Ozawa* who can be regarded as the inventors of SCC. He was one of the members who organized the first open experiment of SCC executed at the campus of the University of Tokyo in 1989, and one of the experts who are well acquainted with the original concept of High Performance Self-Compacting Concrete.

When the author became a guest researcher at the Department of Concrete Structures of the Delft University of Technology, SCC was a topic of interest in the Dutch concrete industry but the development had not been very successfully yet. Many producers were eager to develop it, but the trials seemed to reach a deadlock.

On the other hand, the author had further thoughts on the technology of SCC at the time that he had 4-years experience working for a Japanese general contractor, Kajima Corporation, after his master's degree. There was no doubt that SCC had become practically available in the Japanese construction market and that the number of applications had been increased. However, the mixture designing process of SCC had still, always, included trial-and-error steps and the results in the laboratory mixing test more or less deviated from the results of practical mixing, which meant that additional adjustments were necessary to produce SCC at an industrial concrete plant. It was obvious that there were still some open questions in the SCC technology and one of the main reasons for this situation was a lack of knowledge on the influence of mixing, the influence of chemical admixtures and the mutual relation between them. Therefore, the need for further investigation in this area was clearly felt.

Here, the interests of both the author and the Dutch construction industry came together. It was decided to cooperate with the Dutch industry in order to make SCC practically usable in the Netherlands and, in addition, to investigate the influence of type of mixing and the admixtures. Support was given by the Dutch ready-mix concrete industry. The research project fitted as well in the STW project PPM (Priority Program Materials). That was the starting point of this PhD project in 1997.

## 1.2 AIM AND OUTLINE OF THE PROJECT

In order to fulfill the interest of the Dutch concrete industry, the early development of a prototype Dutch SCC mixture was required. On the other hand, the author also needed to design a basic SCC mixture before starting further investigation. Therefore, the first stage of the project aimed at verifying the producibility of SCC in a laboratory of a Dutch ready-mixed concrete plant applying Dutch local materials. At this stage, the Japanese mixture design method was applied in order to make the fastest progress. Within the scope of this work, a recommendation for a Dutch prototype SCC mixture and a quality control method was targeted.

After the development of the prototype, the research focused on the application of very fine mineral admixtures, so-called "microfillers" as a material for SCC. Nowadays SCC is often required to provide special behavioral characteristics, such as high strength, light weight, low heat, high ductility and so on. Especially a compressive strength higher than 100 N/mm$^2$ is often specified and its impact on the construction market may be considerable. Microfillers might improve the particle size distribution of SCC mixtures and possibly enhance their workability. From this point of view, an investigation of the effect of coal gasification fly ash (CGFA), which is a very fine and round-shaped fly ash which newly appeared on the Dutch market, was considered worthwhile in comparison with the performance of other microfillers, like silica fume and micronized fly ash. This investigation was also of strong interest for the Dutch concrete industry, especially the Dutch fly ash supplier who developed the CGFA. .

After the previously described two-stage contribution to the Dutch concrete industry, the research project shifted to the influence of mixing and chemical admixtures on the behavior of SCC, for the following reason. In the laboratory experiments, performed in the first stage, the Japanese mixture design method was applied in order to accelerate the development while laboratory equipment similar to the Japanese type was used as well. Usually, however, in Dutch concrete laboratories small gravity tilting mixers are used for concrete mixing, whereas in Japan forced mixers of a pan type or horizontal dual axes type are normally used for producing SCC, both in laboratories and at commercial plants. Those mixers have a larger mixing intensity than gravity tilting mixers. On the basis of this background, the author strongly felt the necessity for further investigating the influence of mixing on the mixture proportioning of SCC, for better facilitating the production of SCC in the Netherlands.

As described in the general scope of this research project, the influence of mixing on the mixture proportioning of SCC is still unknown even in Japan. Most of the concrete technologists experienced in producing SCC recognize that the mixture composition depends on the intensity of a mixer given, but they practically adjust the mixtures by trial and error based on their experience. Therefore, an investigation of this subject could provide the necessary information for further rationalization of the mixture design procedure for SCC. This is the main purpose of this project. Within this scope, the influence of chemical admixtures, the type of superplasticizer and the use of a viscosity modifying admixture, were also studied because the mixing efficiency is clearly affected by the type of chemical admixtures used.

## 1.3 RESEARCH STRATEGY AND STRUCTURE OF THIS REPORT

In order to reach the aims as outlined in the previous section, this thesis has been structured according to the following research strategy. It is divided into two parts, the first one (phase-I) being the research and development for the Dutch concrete industry and the second one (phase-II) being an investigation to obtain new knowledge on the influence of mixing and chemical admixtures for the rationalization of the SCC mixture design in general.

Chapter 2 contains a literature survey for both phases mentioned before. The first and the second section of this chapter mainly describe research phase-I, especially focusing on the Japanese development of SCC and the testing methods to evaluate the fresh properties of SCC and the investigations on the rationalization of the mix design. The third section of this chapter refers to research phase-II, in which the past research on mixing, admixtures and their mutual influence on the properties of fresh concrete and mortar is discussed in order to clarify the necessity and significance of this research subject.

According to the first purpose of this project, the development of SCC using Dutch local materials applying the Japanese mixture design method is reported, and the result of the trial is described in detail in Chapter 3.

In Chapter 4, three microfillers, silica fume, coal gasification fly ash and micronized fly ash are investigated as a material for SCC with advantageous performance. The coal gasification fly ash (CGFA) recently appeared as a secondary material for which it is tried to find a satisfactory usage both from an economical and ecological point of view. In this chapter, the competence of CGFA as a material for concrete is studied in detail and the role of microfillers in concrete mixtures is discussed.

The previously mentioned two chapters – Chapter 3 and Chapter 4 – are mainly dealing with research phase-I. The following two chapters – Chapter 5 and Chapter 6 – focus on research phase-II, which is the main subject of this study.

In Chapter 5, the influence of the mixing efficiency on realizing defined properties of fresh SCC is investigated. A number of concrete mixing tests is described with varying mixing procedures and types of mixers and it is claimed that the necessary mixture proportioning for obtaining an SCC with specified characteristics depends on the mixing efficiency. General tendencies are described. Furthermore, a hypothesis for the effect of mixing on the properties of fresh SCC is given to explain what happens in concrete during mixing.

In Chapter 6, the verification of the hypothesis on the mixing efficiency formulated in Chapter 5 is given. A very intensive and well-controlled testing program on flowable cement pastes with dosed superplasticizer, and in some cases a viscosity modifying admixture, is performed in order to clarify the influence of mixing on the properties of the paste phase of fresh concrete, because it is logical to assume that especially the properties of the paste are influenced by the mixing, whereas the aggregate can be considered to be indifferent. On the basis of the results of the experiments, the influence of the mixing efficiency on the properties of the fresh cement paste is investigated in detail and the interaction between the effects of chemical admixtures and mixing intensity is clarified.

Finally, the results and conclusions of this research project are summarized and a direction for future work on popularization of SCC is given in Chapter 7.

The relation between and the categorization of the chapters is schematically shown in Figure 1.1.

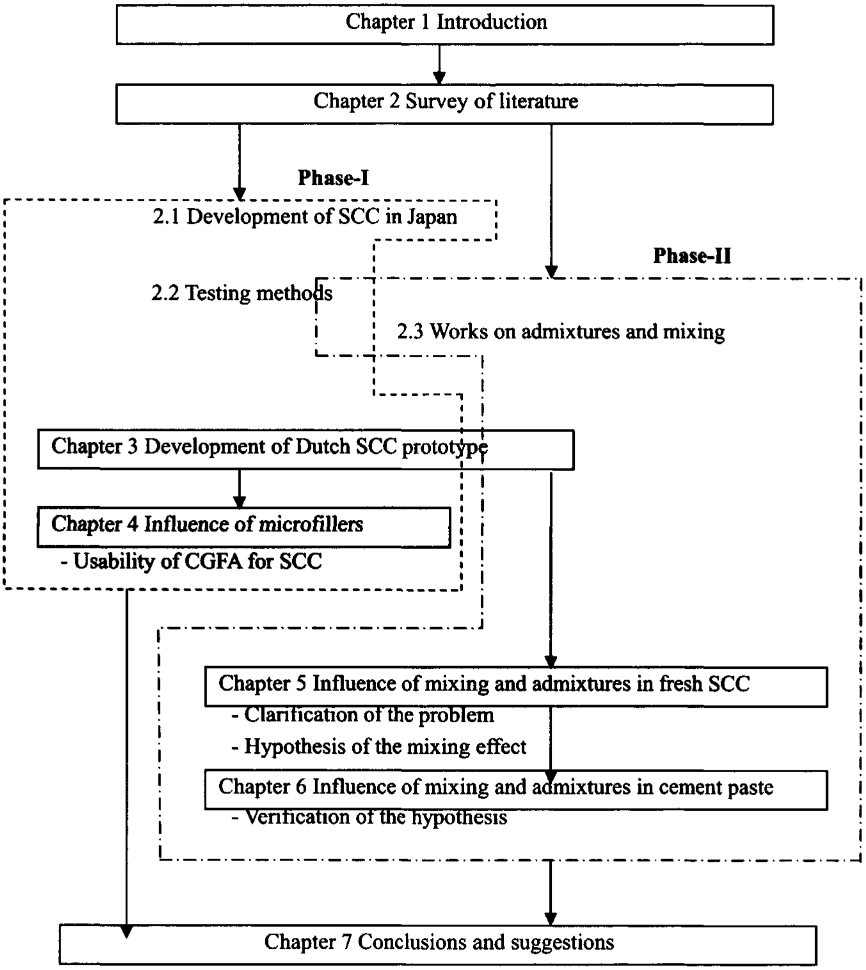


Figure 1.1 Structure of this thesis

# CHAPTER 2
# SURVEY OF LITERATURE

## 2.1 OUTLINE OF THE LITERATURE SURVEY

In this chapter, the results of the literature survey concerning the technology of self-compacting concrete are summarized. According to the two phases of this project defined in Chapter 1, the literature survey can also be roughly subdivided into two categories, one for research phase-I and the other for research phase-II.

Firstly, the Japanese experience on self-compacting concrete is introduced in 2.2. The history of the development, the theoretical background and a basic mixture design method for SCC are described in order to open the readers' eyes, and it is expected to be the basis for research phase-I.

In section 2.3, testing methods for evaluating the fresh properties of SCC are introduced. Most of them are devised in Japan and are closely related to the process of the development of SCC itself. Therefore, this section follows directly after 2.2. Moreover, this section includes some testing methods designed in other countries for the research of SCC or the properties of fresh concrete in general, and also some testing methods are related to research phase-II of this project.

Finally a survey of the past work on admixtures and mixing of concrete is given and summarized in 2.4. The knowledge and information described in this section are expected to help the progress of research phase-II.

## 2.2 DEVELOPMENT OF SELF COMPACTING CONCRETE IN JAPAN

### 2.2.1 History of development [6][7][8]

For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan, even seen as a major problem facing Japanese society. Adequate compaction of fresh concrete is required in order to realize durable concrete structures. However, the gradual reduction in the number of skilled workers in the Japanese construction industry has led to a corresponding reduction in the quality of construction. *Okamura*, who is a former professor of the University of Tokyo and now president of the Kochi University of Technology, therefore emphasized the necessity of a concrete which requires no consolidation works in order to guarantee durable concrete structures in the future. His opinion was presented to the public in the beginning of 1986 for the first time at a meeting of the Japan Cement Association. He had already got the idea to develop self-compacting concrete from the technology of anti-washout underwater concrete.

In the summer of 1988, a prototype of self-compacting concrete was successfully completed by using materials available on the market [3]. *Ozawa*, who is now an associate professor of the University of Tokyo, was given the responsibility for the development and he finalized his PhD. on this work [4]. This prototype proved to have a satisfactory performance with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening and other properties. This concrete was denoted as "High Performance Concrete"

After having succeeded in developing the prototype, the research group conducted an open experiment in the campus of the University of Tokyo in the summer of 1989 (Picture 2.1). More than 100 researchers and engineers attended this experiment and they started intensive research in many places afterwards, especially in the research institutes of the large construction companies.

Picture 2.1 Open experiment in the campus of the University of Tokyo in 1989

In 1991, researchers from 13 general contractors spent a year in the concrete laboratory of the University of Tokyo carrying out a joint research project on self-compacting high performance concrete. In 1993, *Okamura* et al. published a book [8], in which the design method for the mix proportioning of the standard type of self-compacting concrete is explained in detail.

The use of self-compacting concrete in actual structures has gradually increased over the last few years. It has been used for structures such as bridge girders, towers, piers and anchorage blocks, LNG tank slabs and walls, tunnel shafts, culverts and buildings. It has also been used for repair works. Moreover, precast concrete plants are getting prepared to manufacture the products by using self-compacting concrete on a commercial basis mainly in order to eliminate the noise from vibrating machines.

### 2.2.2 Methods for realizing self-compactability

**(1) Properties required for self-compactability** [6]

In order to achieve that a fresh concrete can be filled in a formwork and compacted by self weight without any vibration, the concrete should have a high deformability, comparable to a fluid. To increase the deformability of the paste in the concrete, the water-powder ratio should be increased, otherwise a superplasticizer should be added. On the other hand, self-compacting concrete should also have a sufficient segregation resistance because concrete with a tendency to segregate cannot pass through congested reinforcement due to the interlocking of aggregates. To provide a high segregation resistance, the cement paste should have adequate viscosity. In order to impart the viscosity of the paste, the water-powder ratio should be reduced, or a viscosity agent should be added.

Increasing the deformability means reducing the energy to be consumed by friction in the mixture or at the boundary, when the paste is deformed. Conversely, imparting viscosity means to increase the energy required for deformation. Thus, there is a trade-off between the deformability and the viscosity. If the viscosity of the paste is increased by reducing the water-powder ratio, there is no other choice then using a superplasticizer for higher deformability. Fortunately, the addition of a superplasticizer was found to cause little loss of the viscosity of the paste, whereas it greatly improves the deformability. Thus it was found that there is a range where high viscosity and high deformability coexist in a balanced manner.

**(2) Realizing the coexistence of high deformability and high segregation-resistance** [6]

Whereas a superplasticizer is essential to impart high deformability, it is also important to suitably proportion the aggregate content and to impart suitable viscosity to the paste for providing high segregation resistance. The frequency of collision and contact between aggregate particles increases as the relative distance between the particles decreases. Therefore, the internal stress increases when the concrete is deformed, particularly near obstacles. It has been revealed that the energy required for flowing is consumed by the increased internal stress, resulting in blockage (Figure 2.1) [9]. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than in conventional fresh concrete is effective in avoiding this blockage.

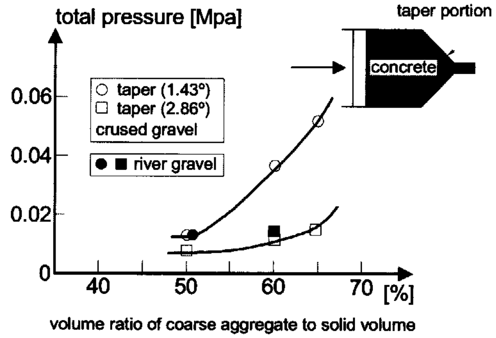


Figure 2.1 Increasing the internal stress due to an increase of the coarse aggregate content (*Nanayakkara* et al. [9])

The reasons for the necessity of imparting the viscosity of the paste are the following. Paste with high viscosity prevents the settlement of coarse aggregate particles, which have a higher specific gravity than the other ingredients, and thereby maintains the uniformity of the concrete. When the concrete is deformed, a paste with high viscosity also prevents localized increments in the internal stress due to the action of coarse aggregate particles with large diameters. It is important to regard concrete as having both liquid and solid properties, because it is a composite of particles of various size and specific gravity.

To realize the coexistence of high deformability and high segregation resistance, the following options were investigated:

**Use of a viscosity agent**

"Anti-washout underwater concrete" is a kind of self-compacting concrete placed underwater, in which segregation is strictly inhibited by a high dosage of a viscosity agent, so as to prevent the cement particles from dissolving in water. This is not suitable for reinforced concrete structures constructed in air, since the viscosity is so high that entrapped air may not easily be released and the concrete may not easily pass through congested reinforcement.

Self-compacting concrete attained by using a viscosity agent was developed and for the first time applied to actual structures by *Takeshima* et al [10]. The balance between the viscosity agent and the superplasticizer is important for increasing self-compactability. However, there is a limit to increase the self-compactability by this method.

**Limiting the volume of aggregate and the water-powder ratio**

Another method is the one in which the volume of aggregate is limited so as to inhibit the collision of aggregate particles near obstacles, while the water-powder ratio by volume is controlled to impart an adequate viscosity to the paste so as to avoid segregation, thereby ensuring self-compactability (Figure 2.2). This method was used to realize the Japanese prototype of self-compacting high performance concrete (Table 2.1).

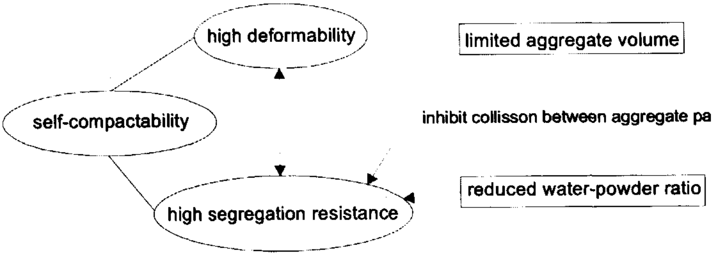


Figure 2.2 Methods of realizing self-compactability by controlling the mix proportion (*Okamura* et al. [6])

Table 2.1 Mix proportion of prototype of high performance concrete

| Slump Flow(mm) | Air (%) | Unit Weight (kg/m$^3$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | W | C | SL | FA | S | G | AD |
| 570 | 2.0 | 159 | 155 | 171 | 202 | 760 | 874 | * |

W = Water, C = Ordinary Portland Cement, SL = Blast Furnace Slag (Blaine: 540 m$^2$/kg)

FA = Fly Ash, S = River Sand, G = River Gravel (Max. Size: 20 mm)

*AD = Superplasticizer 5,544 cc and Cellulose Type Viscosity Agent 20 g

With this method, the powder content is higher than in conventional concrete, due to the increased paste content and the decreased water-powder ratio. A high cement content may cause defects in massive structures. Therefore, a part of the powder is substituted by mineral admixtures as fly ash and ground granulated blast furnace slag, or limestone powder. This is the type of self-compacting concrete used for the anchorage blocks of the *Akashi* Straits Bridge linking the *Honsyu* and *Shikoku* Islands. Its powder content is increased by using a large amount of limestone powder [11].

### (3) Segregation-inhibiting / viscosity-modifying agent

*Shindo* and *Matsuoka* et al. developed an easy method for increasing the level of self-compactability by adding a segregation-inhibiting agent, which is a polymer insoluble in water, to the prototype of self-compacting high performance concrete [12]. Figure 2.3 shows the evaluation of the effect of the segregation-inhibiting agent by the U-shape self-compactability test.

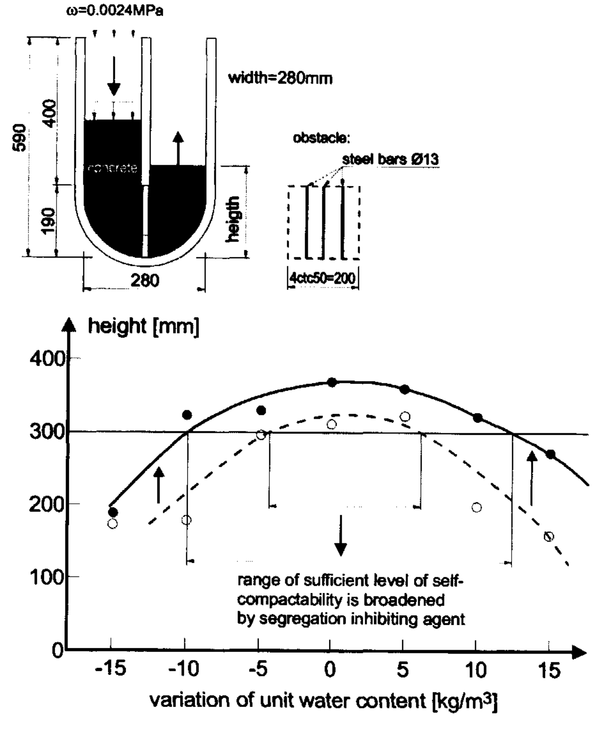


Figure 2.3 Increased level of self-compactability by segregation inhibiting agent ( *Shindo* et al. [12])

In this test, at first the left-hand column is filled with concrete. After the center gate has been opened, the concrete rises through the grid in the right-hand column. The height indicates the degree of self-compactability of the concrete, and a concrete with a rising height over 300 mm is considered to have sufficient self-compactability. The test result indicates that the segregation-inhibiting agent contributes to broaden the range of mixtures with sufficient self-compactability.

*Yurugi* and *Sakata* et al. applied a polysaccharide-based water-soluble viscosity agent, Welan Gum, to self-compacting concrete in order to modify the viscosity [13]. This type of viscosity agent not only inhibits the segregation but also reduces the fluctuation of the concrete properties caused by the variation of material properties and environmental conditions.

### 2.2.3 Mix design of self-compacting concrete (general purpose approach)

**(1) General** [6], [7], [8]

There are numerous solutions for mix proportioning realizing self-compactability. Various proportions are obtained depending on what property is specified first. The proportions currently used may not necessarily be the optimum obtainable from the combination of materials, but rather may simply be one of the many possibilities for achieving self-compactability.

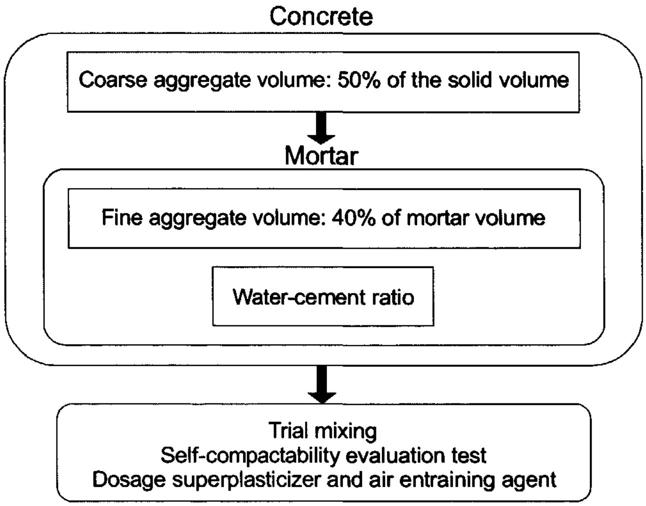


Figure 2.4 Mix design system of general purpose approach (*Okamura* et al. [6], [7], [8])

Assuming general supply from ready-mix concrete plants, a mix design system for general purpose self-compacting concrete has been proposed by *Okamura* et al (Figure 2.4) [6], [7], [8]. This is basically a limited system for the use of Japanese moderate heat Portland cement or low heat Portland cement which includes a high content of $C_2S$. Regarding the application to structures in general, it is appropriate at present to use these types of cement, considering not only the properties of the fresh concrete but also the properties of hardening and hardened concrete, such as heat generation, strength development, drying shrinkage and carbonation. This is a system for which the quality of hardened concrete is normally automatically ensured if the concrete attains self-compactability while being in the fresh state. The mix design is simplified and its reliability is increased by limiting the cement types to be used.

In this system, the target of deformability and segregation resistance is specified at a high level of self-compactability. Self-compactability is therefore ensured for general structures. In the proposed mix design system, the amounts of coarse and fine aggregates are specified at the safe side. A method to determine the amount of coarse aggregate in the concrete or the amount of fine aggregate in the mortar with respect to specific material properties is indicated in this system, so as the way to adapt them to various types of aggregate, as well as to fluctuations during production.

Methods to raise the aggregate content may be developed in the future, if the quantitative evaluation of the effect of the interference between the fine and the coarse aggregate becomes available and the technology of quality control during production is improved. In this system, the water-powder ratio and the dosage of the superplasticizer are not determined until the mortar or concrete is actually mixed. The major reason for this is that the effects of mixing are difficult to deal with quantitatively.

### (2) Volume of coarse aggregate [6]

Figure 2.5 shows an experimental set-up to evaluate the influence of the aggregate on blocking of the concrete [14]. In this experiment, the mortar is an imitation of concrete and the sand is regarded as coarse aggregate. The test result indicates that blocking occurs when the sand content approaches a critical value (graph (a)). When the sand content is beyond this value, blocking always occurs. On the other hand, the critical volume of the sand with regard to blocking increases linearly as the ratio of the hole-diameter to the mean size of the sand increases (graph (b)). Moreover, it is shown that the critical volume with regard to blocking reaches a maximum value when the ratio of the hole-diameter to the mean diameter of the sand exceeds 10. On the basis of this result, it is concluded that when the volume of the coarse aggregate in a concrete exceeds a certain limit, the probability of contact between the coarse aggregate particles drastically increases, causing interlocking, and increasing the possibility of blockage on passing through spaces between reinforcing bars. Therefore, the first point to be considered when designing self-compacting concrete is to restrict the volume of the coarse aggregate below this limit.

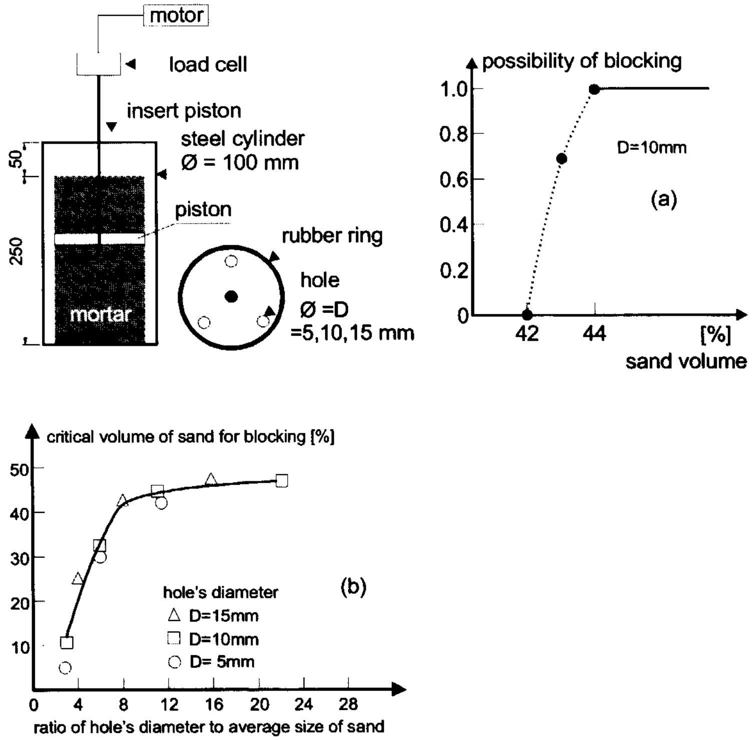


Figure 2.5 Influence of aggregate on blocking of concrete (*Ozawa* et al. [14])

According to this research, this limit is more closely related to the ratio of the volume of the coarse aggregate to its solid volume than to the pure volume. It has also been revealed that the probability of such interlocking is negligible if the ratio is lower than 50% when a proper mortar is used. Therefore, in the proposed system, the content of the coarse aggregate is fixed at 50% of its solid volume (Figure 2.6) [8]. This implies that the volume of the coarse aggregate can be increased if well-graded and well-shaped aggregate is used, because such aggregate has a higher solid volume percentage. The use of river gravel generally permits a larger volume of coarse aggregate than the use of crushed stone.

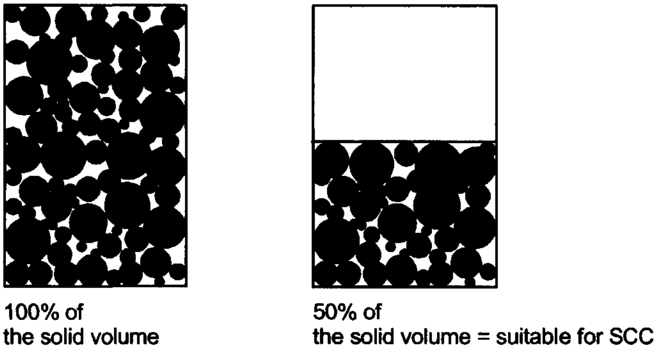


Figure 2.6 Proper coarse aggregate content for self-compacting concrete (*Okamura* et al. [8])

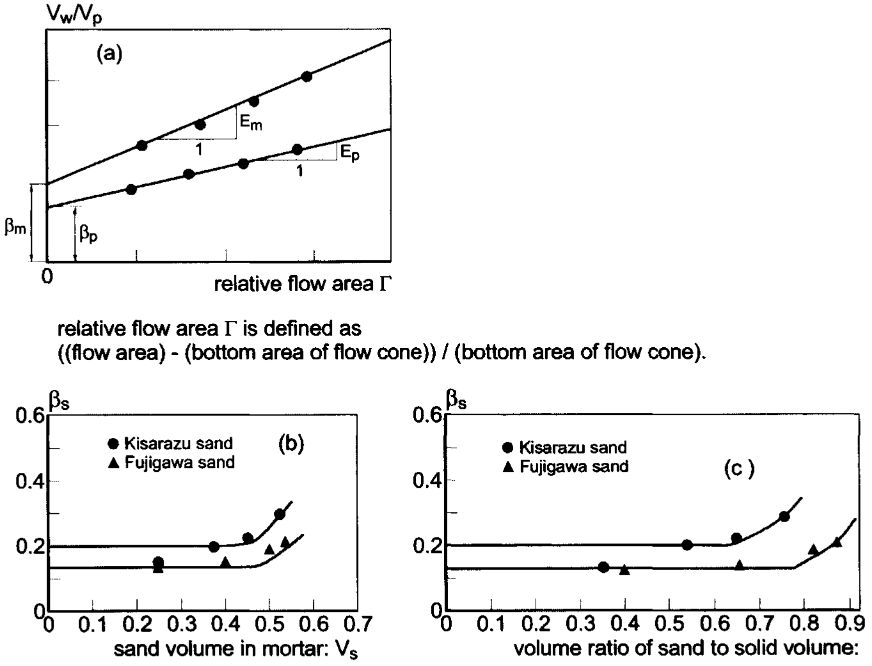
**(3) Volume of fine aggregate** [6]

If the volume of the coarse aggregate is specified, the volume of the mortar can be determined. The volume of the fine aggregate in the mortar is as important as that of the coarse aggregate in the concrete. However, the volume share itself is found to be more critical than the ratio of the volume to its solid volume. Figure 2.7 explains this empirically [15]. The flow area of the paste or the mortar has already been proven to have a linear relationship with the water-powder volume ratio $V_w/V_p$ (graph (a)). The inclination of the lines and the intersection with the vertical axis are represented as $E_p$ or $E_m$ and $\beta_p$ or $\beta_m$ respectively. Here $\beta_p$ is defined as the water-retaining ratio of the powder by volume obtained with the paste flow test, and $\beta_m$ is defined as the water-retaining ratio of the powder and the sand together by volume in the mortar flow test. From these values $\beta_s$ can be defined and calculated as follows:

$\beta_s$ = apparent water-retaining ratio of the sand by volume

$\beta_s = (V_w - \beta_p V_p)/V_s$, where $V_w/V_p = \beta_m$

$\beta_s$ is constant when $V_s$, the volume of sand in mortar, is less than the critical value 0.45 for both two different kinds of sand investigated (*Kisarazu* and *Fujigawa* sand) (graph (b)). This result implies that the interaction between the sand particles apparently influences the flow behavior of the mortar when $V_s$ exceeds the critical value 0.45. However, this critical value becomes different for the *Kisarazu* and *Fujigawa* sand if the sand content is represented by $S/S_{max}$, the ratio of the sand volume in the mortar to the solid volume of the sand (graph (c)). Therefore, it is concluded that the volume share of the sand is a more suitable parameter to design SCC than the ratio of the volume of the sand to its solid volume.



relative flow area Γ is defined as
((flow area) - (bottom area of flow cone)) / (bottom area of flow cone).

Figure 2.7 Influence of sand content on flow of mortar (*Yamaguchi* et al. [15])

If a proper paste is used and the volume of the fine aggregate is below a certain limit, a self-compacting concrete is obtained with no significant direct interlocking of the fine aggregate particles. It has been revealed that self-compacting concrete can be safely produced if the volume of the coarse-grain fine aggregate is set at 40% of the mortar volume (Figure 2.8), which is a lower value than the critical value shown in Figure 2.7(b). Here the coarse-grain fine aggregate is defined as the aggregate in mortar with particles larger than 0.09 mm: the particles smaller than 0.09 mm are regarded to belong to the powder.

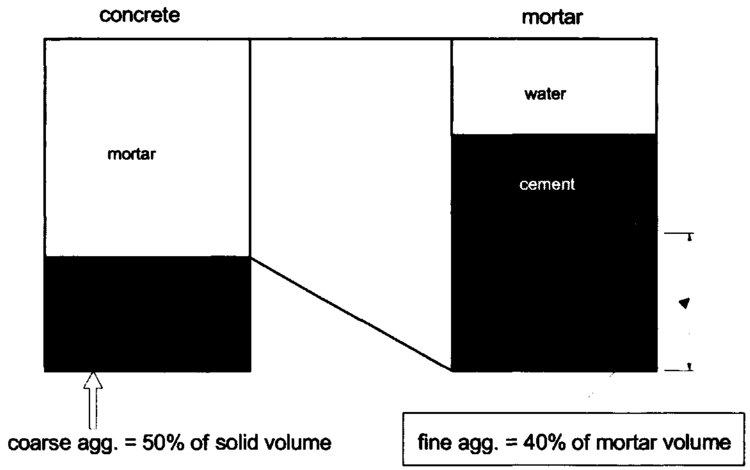


Figure 2.8 Proper fine aggregate content for self-compacting concrete (*Okamura* et al. [8])

**(4) Water-powder ratio and dosage of superplasticizer** [6][7]

When the volume of the aggregate has been specified, the water-powder ratio and the dosage of the superplasticizer have to be determined in order to design the paste. An excessively high water-powder ratio does not cause only segregation of water but also an undesirable reduction of the viscosity, resulting in segregation of the coarse aggregate. Conversely, an excessively low water-cement ratio leads to an extremely high viscosity of the paste, impairing the capability of the concrete to pass through narrow spaces. This occurs even when a superplasticizer is used. A theoretical method for the determination of the water-powder ratio and the dosage of superplasticizer, requiring no tests, has not yet been established. In this design system, the water-powder ratio is generally depending on the properties of the powder and the chemical admixture, and determined after conducting some tests on paste and mortar. Figures 2.9 and 2.10 show the test methods. The relative flow area $\Gamma_m = 5.0$ and the relative funnel speed $R_m = 1.0$ are targeted simultaneously adjusting the water to powder volume ratio ($V_w/V_p$) and the superplasticizer dosage (Sp/P). The value of $V_w/V_p$ determined by this test is evaluated to be adequate for SCC. The value of Sp/P determined in the mortar test may be the adequate value for SCC as well, but it is usually redetermined by the actual mixing of concrete because the appropriate dosage of superplasticizer depends on the efficiency of mixing and the temperature.

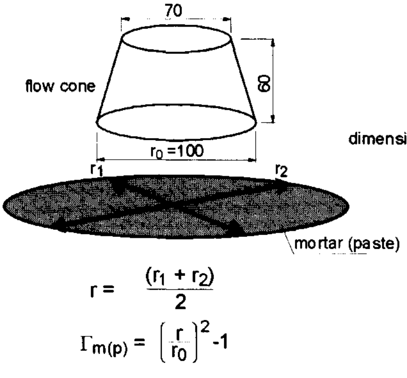


Figure 2.9 Mortar flow test [8]

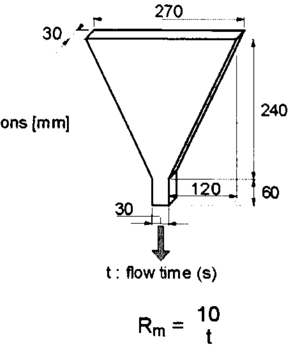


Figure 2.10 Mortar funnel test [8]

### 2.2.4 Rationalization of the mixture design method

After the development of SCC, a lot of researchers and research organizations started investigations to rationalize and simplify the mixture design method. *Ouchi* et al. developed a method to determine an optimized value of the water to powder volume ratio ($V_w/V_p$) and dosage of superplasticizer (Sp/P) by a minimized number of tests on mortar [16]. The method is described in the following.

**(1) A method for the determination of the adequate ratio $V_w/V_p$ by mortar tests**

*Ouchi* et al. found the mutual relation between $\Gamma_m$ and $R_m$ as shown in Figure 2.11. $\Gamma_m$ and $R_m$ are the results of the mortar test described in the Figures 2.9 and 2.10. Each line drawn in Figure 2.11 represents a family of data which is obtained under the condition of a constant $V_w/V_p$ and a varying Sp/P. This relation can be formulated independently of the type of powder materials as

$$R_m = A \cdot \Gamma_m^{0.4} \qquad (2.1)$$

The coefficient $A$ is linearly dependent on $V_w/V_p$ as shown in Figure 2.12, and this relationship can be formulated as

$$A = a \cdot (V_w/V_p) + b \qquad (2.2)$$

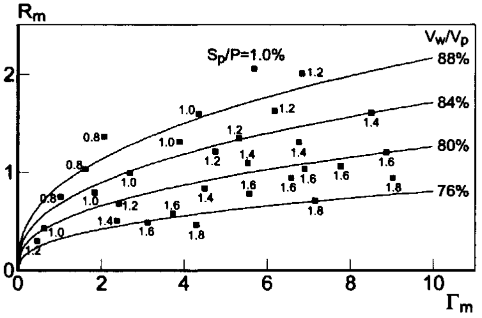


Figure 2.11 Relationship between $\Gamma_m$ and $R_m$ for moderate heat cement mortar [16]

The coefficient *a* represents the inclination of the straight line in Figure 2.12, and varies with the type of powder material. Figure 2.13 shows the relationships between the $V_w/V_p$ and *A* for the different types of powder material used. Generally speaking, the powder materials shown in this figure are categorized into two groups according to the results shown. The first group includes Moderate Heat Portland Cement (MC) and Blast Furnace Slag Powder (BS4000), and its inclination coefficient is approximately 4.0. The other group is Fly Ash (FA) and the inclination coefficient is approximately 6.0. All the powders applied in this survey had a Blaine value between 300-400 $m^2/kg$, and both the superplasticizers used (SP-8S(B) and SP-8N(X3)) are of the polycarboxylic ether type. Therefore, *Ouchi* et al. concluded that the difference of the coefficient *a* is related to the shape, in other words the roundness, of the powder particles: a powder with better roundness has a higher value of the coefficient *a*. In conclusion, an inclination factor $a$=4.0 is recommended to be applied for mortars with ordinary powder materials based on cement in order to estimate the adequate ratio $V_w/V_p$ for SCC.

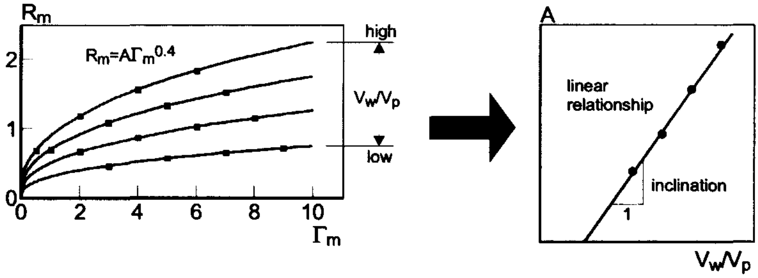
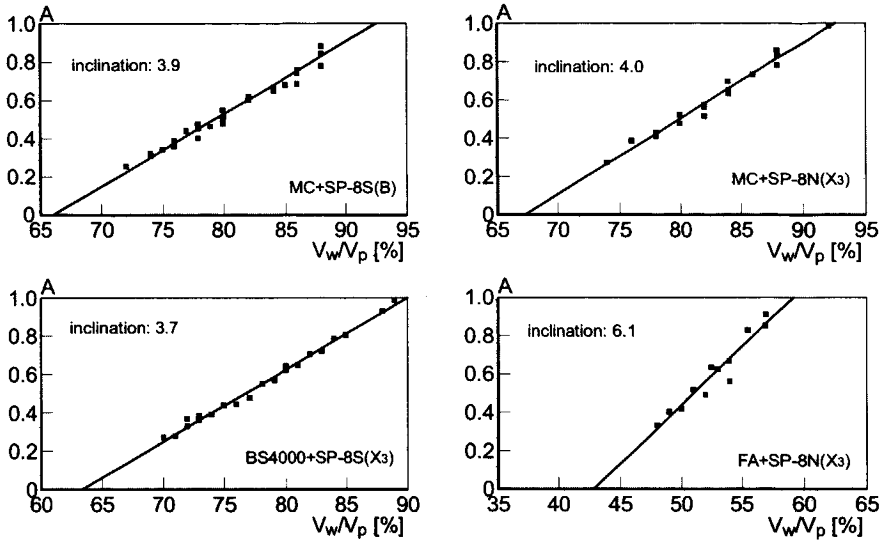


Figure 2.12 Formulation of the relationship between $\Gamma_m$ and $R_m$ with a fixed $V_w/V_p$ [16]



MC = Moderate Heat Portland Cement, BS4000 = Blast Furnance Slag, FA = Fly Ash

Figure 2.13 Relationships between $V_w/V_p$ and $A$ : sand content = 40% [16]

However, for the constant $b$ in the equation (2.2) no simple expression could be found: therefore at least one combination of testing data ($\Gamma_m$, $R_m$) is necessary to find the adequate ratio $V_w/V_p$. For example, when a result of ($\Gamma_{m0}$, $R_{m0}$) is obtained by a mortar flow test and a mortar funnel test with a value of $V_w/V_p=\gamma_0$, a target value of the adequate $V_w/V_p=\gamma_{TG}$ can be calculated by

$$\gamma_{TG} = \gamma_0 - \frac{\dfrac{R_{m0}}{\Gamma_{m0}^{0.4}} - \dfrac{R_{mTG}}{\Gamma_{mTG}^{0.4}}}{4.0} \qquad (2.3)$$

Here, the target values of the mortar tests corresponding to the adequate $V_w/V_p$ are $\Gamma_{mTG}=5.0$ and $R_{mTG}=1.0$ as mentioned in the previous section.

**(2) A method for the determination of the target ratio Sp/P with a mortar test**

In order to design a practical mixture for SCC, it is worthwhile to know the target value of Sp/P in the mortar test to realize $\Gamma_m$=5.0 and $R_m$ =1.0 simultaneously, because it can be the initial input value for the estimation of the adequate Sp/P for the actual concrete production. *Ouchi* et al. introduced a method to determine the target value Sp/P with a few mortar tests. They found that the ratio of $\Gamma_m/R_m$ is almost constant with variation of $V_w/V_p$ on the condition that Sp/P is constant (see Figure 2.14).

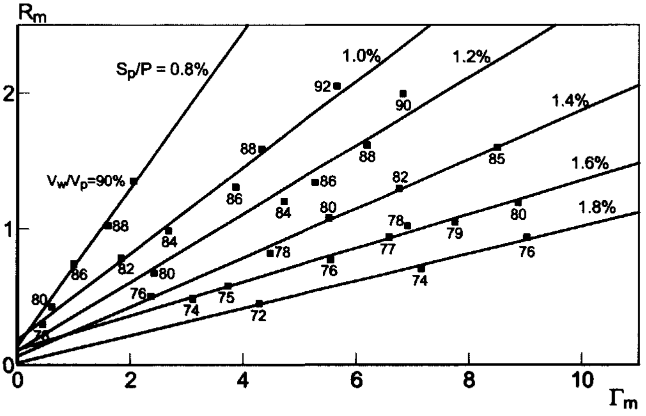


Figure 2.14 Relationship between $\Gamma_m$ and $R_m$ with fixed values of *Sp/P* [16]

The inclinations of the $\Gamma_m$-$R_m$ lines are independent of $V_w/V_p$, and a larger Sp/P results in a larger value of $\Gamma_m/R_m$. On the basis of this relation, it is concluded that the value of $\Gamma_m/R_m$ is a useful parameter to evaluate the relative effect of a superplasticizer. When the mortar property of $\Gamma_m$=5.0 and $R_m$ =1.0 is targeted, the target value of $\Gamma_m/R_m$ is 5.0. If the result of the first trial of the mortar test shows a value $\Gamma_m/R_m<5.0$, a larger Sp/P should be applied for the second trial. If a value $\Gamma_m/R_m>5.0$ is obtained, Sp/P should be reduced for the next trial. This method can minimize the number of trials and errors to determine the target value Sp/P. Furthermore, the value of $\Gamma_m/R_m$ is applied to evaluate the dispersibility of the superplasticizer in the later investigations [17] [18].

### 2.2.5 Considerations for the mechanism of self-compactability

SCC differs in composition from conventional concrete in that excess paste is added. Figure 2.15 shows the outline of the excess paste theory [19]. By this excess paste the aggregate particles are surrounded by a very thin layer of paste, which reduces the internal friction between the aggregate particles when the concrete flows. The surrounding ("smearing") layer must be not too thin, because otherwise the friction is too large, but on the other hand not too thick, because then the friction is too low and the mixture segregates.

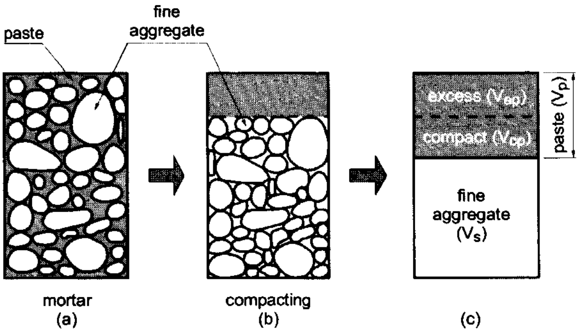


Figure 2.15 Outline of the excess paste theory [19]

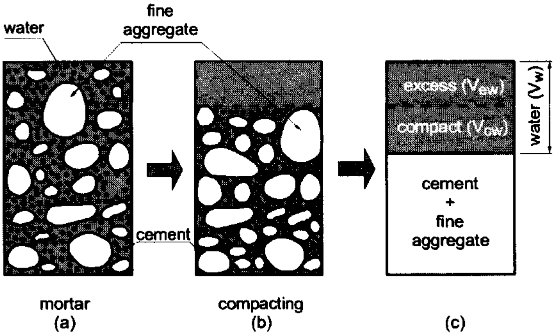


Figure 2.16 Principle of the excess water [19]

The same applies on a lower level to the paste itself. Figure 2.16 shows the principle of excess water in the water layer model [19]. The powder particles are surrounded by a thin water layer with the same function.

Self-compacting concrete can be designed by just adding sufficient paste, but this could mean unfavorable properties in the hardened state (too low E-modulus, too large shrinkage etc.). The principle of the Japanese mix design method of the general-purpose approach is a way to arrive at an appropriate volume of paste and thickness of the water layers. Of course the viscosity of the paste layers has an influence as well. Here the role of superplasticizer comes in. The Japanese mix proportions are designed to lead to properties which are suitable for the Japanese demands. Those are probably useful also in other countries. However, other proportions could be appropriate as well in other countries where different qualities of materials exist and different properties of concrete are required.

## 2.3 TESTING METHODS TO EVALUATE THE PROPERTIES OF FRESH SCC

### 2.3.1 Introduction

There are some properties of fresh SCC which are required to be evaluated by particular testing methods. The following three properties are regarded as the most important criteria for self-compactability.

1) Deformability
2) Segregation resistance
3) No-blocking property

However, these properties are not always independent. They are even more or less interacting. For example, the definition of deformability includes the deformation capacity, in other words the ultimate deformability, and the deformation velocity. The deformation velocity is related to the viscosity of the mixture, but the viscosity of the mixture naturally governs the segregation resistance between the paste (or mortar) and the aggregate. The segregation resistance cannot be defined only by the viscosity of the mixture, but should also depend on the amount and the size of the aggregate. The no-blocking property is dominated by the deformability, the segregation resistance and the boundary conditions of the structures where concrete is placed.

As mentioned before, the superficial properties of fresh concrete are normally correlated. Therefore it is very difficult to exactly categorize the testing methods according to the individual properties of the SCC.

From this point of view, some testing methods which are frequently used for evaluating the fresh properties of SCC are dealt with in the following sections and it is explained what those methods can measure or evaluate. The methods are not categorized according to the evaluated properties, because a testing method usually evaluates various aspects of the fresh concrete, and the aspects often overlap with the result of other testing methods.

### 2.3.2 Slump flow test

The slump flow test is one of the most popular testing methods for evaluating the properties of SCC because the procedure and the apparatus are comparatively simple.

Figure 2.17 shows the slump flow test schematically [8][20]. The following characteristic values are obtained from this test:

a) Slump flow value (ultimate spread diameter)
b) 500 mm flow time (flowing time from initial diameter 200mm to 500mm)
c) Final flow time (flowing time from cone removing to flowing completion)
d) Degree of segregation (eye observation)

The slump flow value is a useful index to evaluate the deformation capacity of a highly-flowable fresh concrete. It corresponds well to the rheological parameter yield stress supposing the concrete acts as a Bingham fluid.

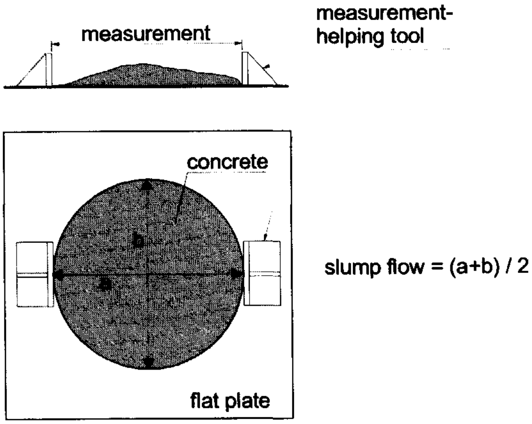


Figure 2.17 Slump flow test [20]

The 500 mm flow time or the final flow time is frequently used to evaluate the viscosity of a highly-flowable fresh concrete. The final flow time is more determined by the final slump flow value and is more subjective to human judgment than the 500 mm flow time. Therefore, the 500 mm flow time is more useful for the evaluation of the viscosity of the mixture. However, the 500 mm flow time is also related to the slump flow value (deformation capacity). For instance, a larger slump flow tends to result in a shorter 500 mm flow time even if the viscosity of the mixture is constant. In other words, it cannot estimate the viscosity of the mixture independently of the potential deformation capacity. Fundamentally, the physical meaning of the viscosity of fresh concrete should be defined like the rheological parameter plastic viscosity which is independent of the yield stress of the Bingham fluid. However, the 500 mm flow time always relates to the slump flow value which almost represents the yield stress of the mixture. Therefore, the 500 mm flow time cannot alone represent the viscosity of the fresh concrete, and it should be noticed that the 500 mm flow time can evaluate the viscosity of the fresh concrete relatively only when the potential deformation capacity, i.e. the slump flow value, of the tested mixtures is controlled. In such a case, the 500 mm flow time is a useful index for the relative evaluation of the viscosity of SCC.

The slump flow test is one of the easiest methods to evaluate the segregation resistance of a highly-flowable fresh concrete by visual observation, because coarse aggregate particles tend to stay at the center of the spreading circle if the segregation resistance is not sufficient. However, the slump flow test is not suitable for a quantitative estimation of the segregation resistance.

### 2.3.3 V-funnel test

Figure 2.18 shows the apparatus of the V-funnel test [8][20]. There are two types of V-funnel apparatus standardized in Japan according to the size of the bottom opening mouth: one is 65×75 mm and the other is 75×75 mm.

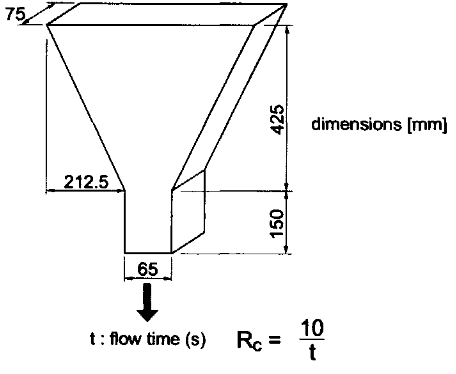


Figure 2.18 V-funnel apparatus [20]

The funnel flow time t (sec.) or the relative funnel speed $R_c$ is the principal information obtained by this test. The physical meaning of these indexes includes several aspects of highly-flowable fresh concrete. In order to understand the significance, it is important to exactly grasp the testing condition applied.

In the case that the volume and the size of the coarse aggregate particles are sufficiently small relatively to the size of the opening mouth of the V-funnel apparatus, the collision and the interaction among the coarse aggregate particles is supposed to be negligible for the funnel flowing characteristics of the fresh concrete. Under such a condition, the funnel flow time t (sec.) or the relative funnel speed $R_c$ can be considered as the indexes representing the viscosity of the mixture. However, the funnel flow time is also affected by the potential deformability, in other words the deformation capacity, of the concrete as well as the 500 mm flow time, because a larger slump-flow concrete tends to result in a shorter funnel flow time even when the viscosity of the mixture is constant. Therefore, the funnel flow time or the relative funnel speed is not possible to represent the viscosity of the mixture independently of the deformation capacity. It can relatively evaluate the viscosity only under the condition of a constant slump flow value. In such a case, a longer funnel flow time represents a higher viscosity of the mixture and it directly relates to a better segregation resistance.

In the case that the volume and the size of the coarse aggregate particles are relatively large for the size of the opening mouth, the collision and the interaction among the coarse aggregate particles are dominant for the funnel flowing characteristics of the fresh concrete. Under such a condition, the V-funnel test is useful to evaluate the narrow-opening-passing ability of a highly-flowable fresh concrete. In this range of mixture composition, a less viscous mixture occasionally results in a longer funnel flow time because of the enlarged interaction of the coarse aggregate particles. In other words, the V-funnel test does not simply evaluate the viscosity of the mixture. However a shorter funnel flow time, or a larger relative funnel speed, mostly represents a better narrow-opening-passing ability and the indexes are useful to be evaluated. One of the influential factors for the V-funnel test resulting under an aggregate-dominant condition is the viscosity of the mixture as mentioned already. A too small viscosity tends to result in a long funnel flow time due to the interaction of the coarse aggregate particles. A too large viscosity also results in a long funnel flow time due to the slow deforming velocity. A moderate viscosity is required to minimize the funnel flow time. The deformation capacity (slump flow), the size distribution of the coarse aggregates, the volume of the coarse aggregate and the shape of the coarse aggregate are also influential factors dominating the V-funnel test result.

Figure 2.19 shows an example of the evaluation of a V-funnel test result [21]. The figure indicates that the combination of the slump flow test and the V funnel test is useful to evaluate the filling capacity of SCC in general. In this figure, the following indexes are used for the evaluation.

Relative flow area = $(SF/600)^2$ SF: slump flow value (mm)

Relative funnel velocity = 5/t t: V-funnel flow time (sec.)

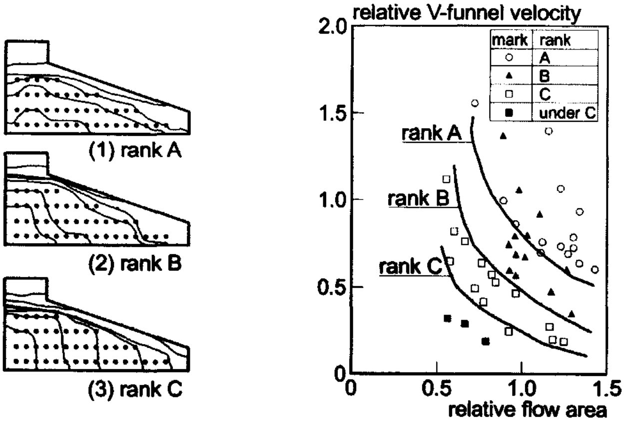


Figure 2.19 Evaluation of self compactability by the result of a V-funnel test and a slump flow test [21]

### 2.3.4 Filling vessel test

In the early stage of the development of SCC, some kinds of filling vessel tests which model small scale structures with congested reinforcement were developed and used to evaluate the self compactability of fresh concrete. Figure 2.20 is a typical example of such a testing apparatus [8]. The largest advantage of this kind of method is the easiness to visually understand the self compactability of fresh concrete. A judgment of "good or bad" as SCC can be clearly made by observing the flowing and filling behavior of the fresh concrete. The test is aimed at evaluating both the narrow-opening-passing ability and the self-leveling ability simultaneously. The balance between the two properties can be controlled by changing the clearance between the bars. The concrete sample is cast gradually and the previously placed concrete is moved by the pressure of the following concrete. In case that the previously placed concrete has already stuck due to its insufficient narrow-opening-passing ability, the newly placed concrete flows beyond the old concrete. The possibility of eye-observation of the concrete flowing behavior in a situation similar to the actual condition is a typical advantage of this type of test method. Therefore, the apparatus shown in Figure 2.20 was useful and often applied in the early period of SCC development.

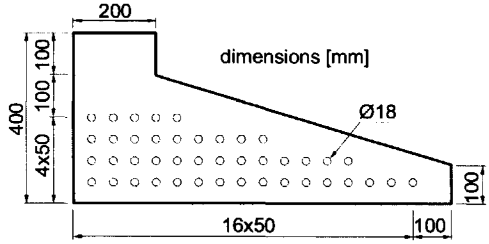
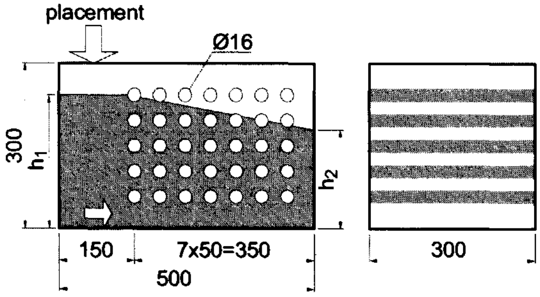


Figure 2.20 Example of filling vessel test apparatus [8]



$$\Delta h(mm) = h_1 - h_2$$

$$F(\%) = (h_1 + h_2) \times \frac{350}{2} / (h_1 \times 350) \times 100 = \frac{h_1 + h_2}{2h_1} \times 100$$

Figure 2.21 Another example of a filling vessel test [23]

However, the filling vessel test method has too many vital disadvantages to be a common quality control test. For example:

a) The labor needed for the test is relatively intensive due to the necessary volume of concrete.
b) The testing time is relatively long due to the procedure for pouring the concrete.
c) The quantitative evaluation of self-compactability is difficult.

The apparatus shown in Figure 2.21 which is a modification of the apparatus shown in Figure 2.20 is another example of this type of filling vessel test [22][23]. It is aimed to make a quantitative evaluation possible.

### 2.3.5 Vertical mesh-pass test

Figure 2.22 shows the apparatus of the vertical mesh-pass test [8]. This is a test method, which was applied in the early stage of the SCC development. The method aims at estimating the narrow-opening-passing ability quite specifically. The narrow-opening-passing ability is evaluated by the passing volume ratio of the placed sample. The passing speed is also an index for the evaluation when the passing ratio is 100%.

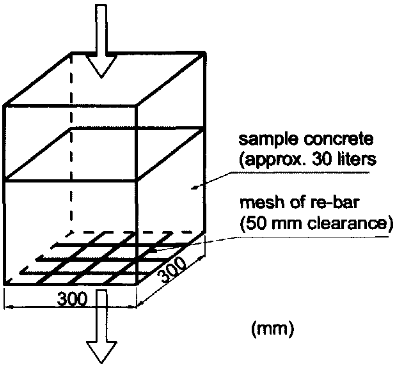


Figure 2.22 Vertical mesh-pass test [8]

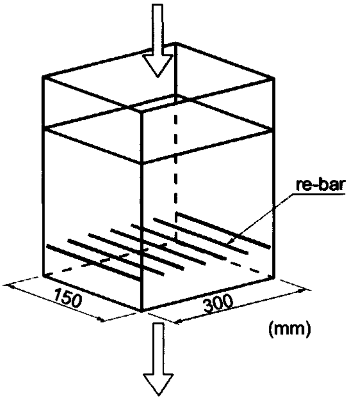


Figure 2.23 Parallel bar pass test [8]

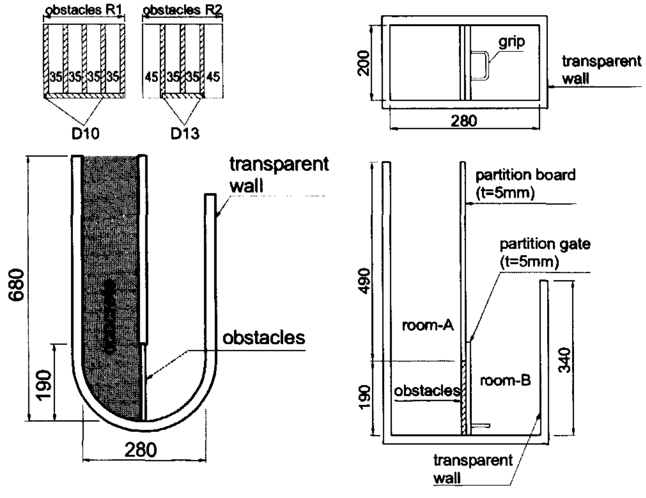
Before the test execution, a certain amount of the sample concrete is filled in the box which equips the mesh at the bottom and is placed on the flat surface to avoid leaking of the sample. When the sample concrete is filled in, the apparatus is raised by a crane and the sample concrete starts flowing. Then, a higher head pressure is given to the sample concrete than in the filling vessel test mentioned above. It means that the vertical mesh-pass test evaluates the narrow-opening-passing ability of the fresh concrete under a higher pressure level than the filling vessel test.

The apparatus was also often used to understand the mechanism behind the SCC behavior but it is not suitable as a common quality control method due to the relatively large sample volume and the large time consumption.

Figure 2.23 shows a modified apparatus which equips parallel bars and requires a smaller sample volume of concrete than the mesh-pass test. The result of this test method has a strong correlation with the result of the mesh-pass test.

### 2.3.6 U-shape and box-shape self compactability test

Figures 2.24 and 2.25 show the sets of the U-shape test apparatus and the box-shape test apparatus [20]. Both methods were developed to evaluate the narrow-opening-passing ability of a highly-flowable fresh concrete under a particular head pressure, which includes the deformability and the no-blocking property. The U-shape apparatus was developed [12] before



U-shape apparatus

box-shape apparatus

Figure 2.24 U-shape and box-shape test apparatus (obstacles are common for both tests) [20] the box-shape apparatus which appeared as a modification of the U-shape apparatus with a severer flowing resistance due to the more angular shape.

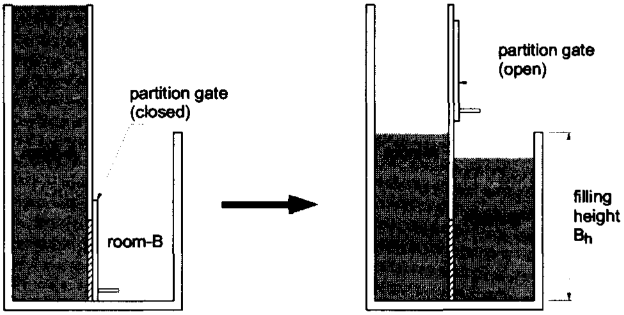


Figure 2.25 Testing with box-shape (U-shape) apparatus [20]

The apparatus is divided into 2 compartments. The fresh concrete sample is filled into room-A of the apparatus. An outlet to let the concrete flow from room-A to room-B is provided at the bottom part between room-A and B, with a grid of reinforcement installed to simulate the reinforcing area. A partition gate is installed in order to prevent the concrete to flow from room-A to room-B during filling the concrete sample into room-A. The gate will be opened when room-A has been fully filled with the concrete sample to let the concrete sample flow to room-B through the installed reinforcement cage. After the flow stops, the height of the concrete in room-B is measured from the bottom of the apparatus to the surface of the concrete. The filling height is used to evaluate the narrow-opening-passing ability of the concrete tested. The concrete with a larger value of the filling height is evaluated to have a better narrow-opening-passing ability. Additionally, the time during which the concrete flows is measured and used to evaluate the viscosity of the mixture.

When an evaluation is made of the result of this test method, the following aspect should be noticed. As well as the test result of the V funnel test, the physical meaning of the filling height is influenced by the mix composition of the concrete tested. For example, when the size and the volume of the coarse aggregate are sufficiently small compared to the clearance of the installed bars, the filling height is strongly dependent on the deformation capacity, i.e. slump flow value, of the sample concrete. Then, the segregation resistance hardly governs the value of the filling height. In such a case, the flowing time (flowing speed) in the U-shape or the box-shape apparatus well represents the viscosity of the mixture that controls the segregation resistance.

On the other hand, when the size and the volume of the coarse aggregate are relatively large compared to the clearance of the installed bars, the collision and the interaction of the coarse aggregate particles dominantly affect the narrow-opening-passing ability. In such a case, a concrete with a tendency to segregate often results in a low filling height of the U-shape or the box-shape test even though the concrete has a large slump flow value. Moreover the flowing speed tends to be low due to the interaction of the coarse aggregates, even if the viscosity of the mixture is not so large.

A common feature of the vertical mesh-pass apparatus and the U-shape or the box-shape apparatus is the installation of reinforcement to produce a number of narrow openings to simulate the reinforcing area. One may try to select the spacing according to a real situation in the structure. However, it is not practical to always vary the condition of the apparatus. Consequently, it is popular and conservative to select the clear spacing of the reinforcement based on the common minimum clear spacing allowed by each country's design specification (the minimum clear spacing between the bars depends on the maximum size of the aggregate and the minimum dimension of the member, etc.) and the overall density of the reinforcement in the members. According to the "Recommended Guidelines for Self-Compacting Concrete" issued by the Japan Society of Civil Engineers in 1998 [20], the ranks of self-compactability are classified as shown in Table 2.2 concerning the clearance of the bars in the U-shape or the box-shape apparatus that the concrete can pass with a filling height of 300mm or more.

Table 2.2 Relation between rank of self compactability and result of U- or Box-shape test [20]

| Rank of self compactability | | 1 | 2 | 3 |
|---|---|---|---|---|
| Structural condition | Minimum clearance of reinforcement (mm) | under 60 | 60 - 200 | over 200 |
| | Quantity of reinforcement (kg/m$^3$) | over 350 | 100 - 350 | under 100 |
| Filling height in U- or box-shape test (mm) | | over 300<br>(obstacles R1) | over 300<br>(obstacles R2) | over 300<br>(no obstacles) |

### 2.3.7 L-shape flow test

Different kinds of L-shape flow tests have been developed so far. In a rough classification, there are two types of L-shape flow apparatus with regard to their principles. One type of L-shape apparatus does not equip obstacles on the flowing way of sample concrete. Another type commonly provides some reinforcing bars to simulate narrow openings.

Figure 2.26 shows an example of the former type of L-shape apparatus [20]. This apparatus is applicable to a concrete whose maximum size of the aggregate does not exceed 25 mm. The available information from this test is:

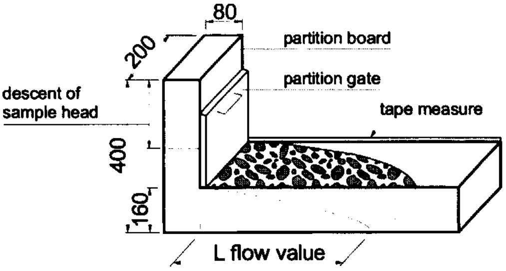


Figure 2.26 Example of L-shape apparatus (no obstacles) [20]

a) L-flow value (ultimate flow distance)
b) time to particular flow distance (flow speed)
c) time to flow completion
d) descent of sample head
e) degree of segregation (eye observation)

Except peculiar cases, the results of this type of L-shape flow test correspond well with the results of the slump flow test. The L-flow value represents well the deformation capacity of the concrete sample as well as the slump flow value does. The descent of the sample head has a similar physical meaning as the slump value (descent of the sample head in the slump flow test or the slump test). In other words, the slump flow test evaluates the two-dimensional flowability of the sample concrete under free conditions and this type of L-shape flow test evaluates the one-dimensional flowability under a directionally restrained condition.

However, in the case that the sample concrete has a strong tendency to segregate and/or the volume of the coarse aggregate in the mixture is relatively large, it is possible that the concrete flow is stopped by blocking at the open gate. When this phenomenon occurs, the result of the L-flow value does not correspond to the result of the slump flow test.

Examples of the latter type of L-shape apparatus which equip some bars to install narrow openings are shown in the Figures 2.27 and 2.28. The L-shape test shown in Figure 2.27 [24] is developed to particularly evaluate the narrow-opening-passing ability. A larger value of h, the descent of the sample head, indicates a better narrow-opening-passing ability of the concrete tested.

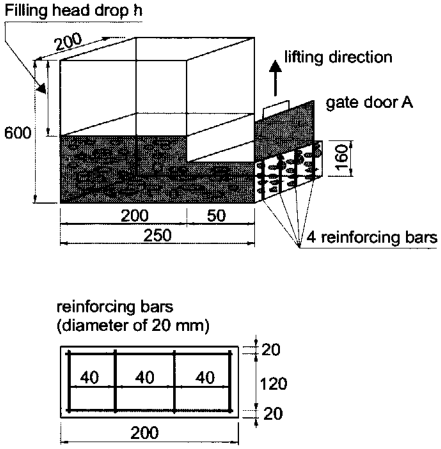


Figure 2.27 Example of L-shape apparatus (with obstacles) [24]

The other type of L-shape test shown in Figure 2.28 [25] aims at simultaneously evaluating the deformability and the narrow-opening-passing ability by a single test apparatus. The flow time to a particular distance (200 and 400mm) is used to evaluate the deforming velocity. The value of H2/H1 (see Figure 2.28), the so-called blocking ratio, is used to quantify the narrow-opening-passing ability that includes the deforming capacity and the blocking property. The principle of this testing method is almost the same as that of the U-shape or box-shape test method.

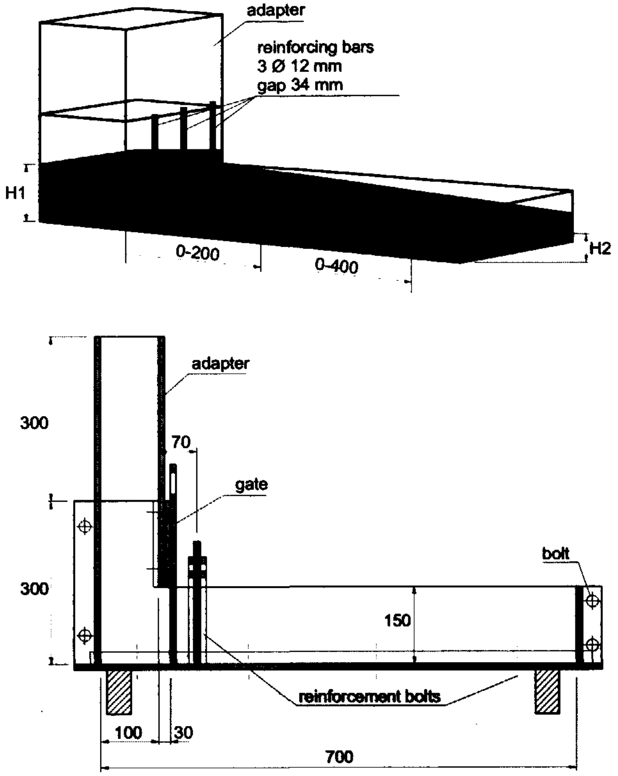
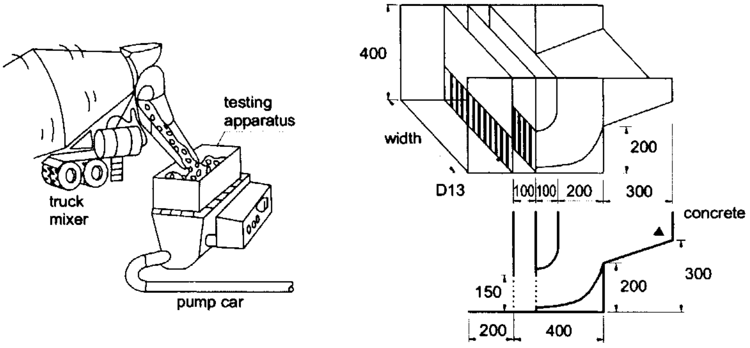


Figure 2.28 Example of L-shape apparatus [25]

### 2.3.8 All concrete acceptance test

SCC is placed without mechanical vibration often where the consolidation work is difficult. Under this condition, a small volume of concrete with insufficient self-compactability is possible to be a fatal cause for spoiling the quality of the total structure. Therefore, it is strongly desirable to evaluate the self-compactability of all concrete before placing in the formwork. However, the test methods mentioned in the previous sections are not suitable for this purpose.

In order to solve this problem, an acceptance test as shown in Figure 2.29 was developed [26]. This test method enables the evaluation of the self-compactability (narrow-opening-passing ability) of all concrete continuously and the detection of inadequate self-compactability before casting (or pumping) the concrete.



Outline of acceptance test

Testing apparatus

Figure 2.29 All concrete acceptance test [26]

### 2.3.9 Tests on mortar

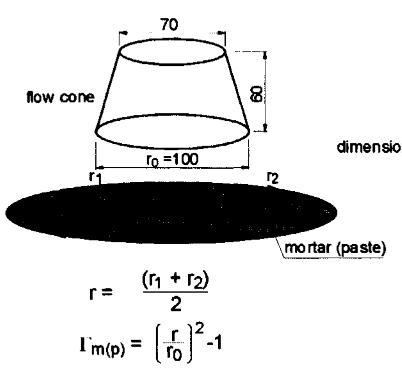
On the basis of the SCC mixture proportioning, the following conditions are an important subject.

a) The size and the volume of the coarse aggregate should be adequate for the boundary condition of structures where the concrete is placed concerning the narrow-opening-passing ability.

b) The mortar in the concrete should have a sufficient deformability, since it governs the deformability of concrete, and an adequate viscosity, since it governs the segregation resistance between the coarse aggregate and the mortar itself.

From this point of view, evaluation methods to determine the properties of the mortar are required in order to design SCC properly and several kinds of test methods have been developed.

Figure 2.30 schematically shows the mortar flow test [8]. The ultimate spread diameter of flowing mortar is measured under a no-vibrating condition. The relative flow area $\Gamma_m$ is calculated using the result of the spread diameter and used to evaluate the deformability (deformation capacity) of the mortar. This test is applied also for paste to evaluate the property of the powder materials.



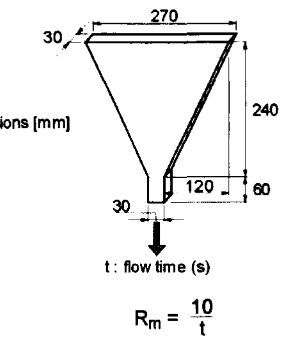


Figure 2.30 Mortar (paste) flow test [8]

Figure 2.31 Mortar funnel test [8]

Figure 2.31 shows the mortar funnel test apparatus [8]. The viscosity of the mortar is evaluated by this testing method. The flow time t or the relative funnel speed $R_m$ is used as an indicator for the viscosity.

Both test methods mentioned above aim at evaluating the properties of the mortar supposing that it is a homogeneous viscous fluid. In the case that the volume of the fine aggregate in the mortar is not too large and the influence of the interaction between the fine aggregate particles is negligible for the characteristics of the flowing mortar, this supposition is acceptable. However, when the amount of the fine aggregate in the mortar exceeds a particular value, the interaction between the particles is not negligible and the flowing behavior of the mortar is strongly influenced by it. From this point of view, these testing methods are useful also to evaluate the adequate amount of fine aggregate in SCC. Normally, the amount of the fine aggregate is designed to avoid a strong interaction between the fine aggregate particles to realize a high deformability of SCC.

### 2.3.10 Rheology test

#### (1) Basic rheological principles [27]

Liquid and suspensions set up a resistance to deformation which depends on the type of loading. This resistance can be measured in viscometers by a stationary shear test under laminar flow conditions and provide evidence about the structure and viscosity of the liquid or suspension. Viscometers of many different designs are used to determine rheological parameters. They are divided into capillary viscometers, falling-body viscometers and rotational viscometers on the basis of their various modes of operation. Rotational viscometers, with which the dependence of the shear stress $\tau$ [N/m$^2$] on the shear rate D [1/s] can be measured, are suitable for investigating suspensions. In the simplest case the measured flow curve is a straight line which passes through the origin of the coordinate system (Figure 2.32 A) and can be described by the Newtonian flow law.

$$\tau = \eta \cdot D \tag{2.4}$$

The proportionality factor $\eta$ [N·s/m$^2$] is known as the dynamic viscosity and corresponds in the shear diagram to the cotangent of the gradient $\alpha$ of the straight line. Fluids which obey this flow law are known as "Newtonian fluids". In this case the viscosity is a material constant , which is dependent only on temperature and pressure.

Many liquids and suspensions show varying degrees of deviation from the Newtonian flow behavior. For instance, pseudoplastic liquids become more mobile with increasing the shear rate, while with dilatant liquids the resistance to deformation rises with increasing the shear rate. The viscosity of these types of liquids is not a material constant, but is expressed as apparent dynamic viscosity $\eta' = \cot \alpha'$ (Figure 2.32 A); its value depends on the shear stress.

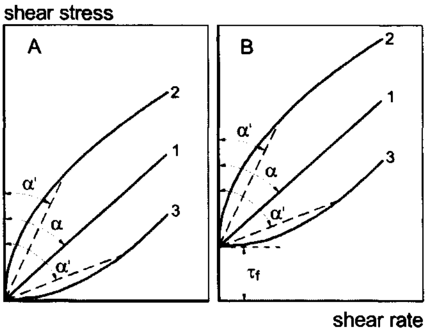


Figure 2.32 Flow Curves for 1: Newtonian Liquid, 2: Pseudoplastic Liquid and 3: Dilatant Liquid, "A" without and "B" with Yield Value [27]

Suspensions often only begin to flow when a minimum shear stress is exceeded. The flow curves therefore do not pass through the origin of the coordinate system, but are displaced along the shear stress axis. The extent of the shift is designated as the yield value $\tau_f$. If the flow behavior of the liquid above the yield value corresponds to that of the "Newtonian fluid" it is referred to as a Bingham fluid of constant dynamic viscosity $\eta_B$, and its flow behavior (Figure 2.32 B) can be described by the equation

$$\tau = \tau_f + \eta_B \cdot D \qquad (2.5)$$

If the flow curves above the yield value show a pseudoplastic or dilatant flow behavior, these liquids are known as a pseudoplastic or dilatant Bingham fluid for which an apparent dynamic viscosity $\eta'_B$ has also been defined , the value of which changes with the shear stress (Figure 2.32 B).

It is known that cement paste behaves as a pseudoplastic Bingham fluid in viscosity investigations where the shear stress is raised in steps. This means that the agglomerated cement particles can take shear stresses below the yield value without deformation and that above the yield value the flow resistance decreases with increasing shear rate.

**(2) Viscometer for paste and mortar** [27]

A computer-controlled rotational viscometer has been developed for measuring the rheological characteristics of cement pastes and mortars. The viscometer consists of a rotating measuring vessel to carry the cement paste. A double-walled measuring vessel (see Figure 2.33) makes it possible to set the temperature of the test material using a cryostatic temperature regulator. A measuring paddle is immersed in the rotating cement paste. The measuring paddle is attached to a torque measuring head. The viscous resistance of the rotating cement paste generates a torque (shear resistance) at the measuring head via the fixed measuring paddle; this is electronically recorded and transmitted to a computer. The rotational speed of the measuring vessel can be varied by computer control. The shear resistance T [N·mm], measured as a function of the rotational speed of the measuring vessel N [rpm], is recorded.

A trapezoidal paddle, with a shape designed so that segregation of the paste during measuring is largely avoided, is equipped (see Figure 2.33). Owing to the geometry of the measuring vessel and paddle, this does not provide an ideal rotationally symmetrical shear surface and the shear process takes place in a three-dimensional perturbation zone, but it has been shown in [28] that the torques measured are directly proportional to the yield value and viscosity of the suspensions investigated. So the shear resistance on a variation of load can be expressed in analogy with the following equation:

$$T = g + h \cdot N \qquad (2.6)$$

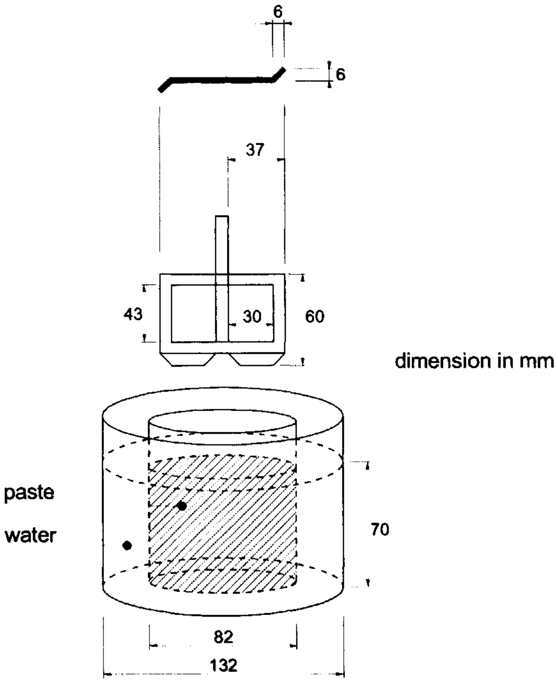


Figure 2.33 Sketch of measuring vessel and paddle of a viscometer for paste

The variables $g$ and $h$ are designated as the relative yield value [N·mm] and the relative viscosity [N·mm·min] respectively and can be calculated on removal of the load with the equation (2.6) from the direct measurements of the shear resistance T. If the apparatus constants of the rotational viscometer used are determined by means of comparative measurements on a liquid with known rheological properties, the relative measurements of yield value and viscosity can be converted to absolute material parameters and this allows measurements from various viscometers to be comparable. However, the variables $g$ and $h$ calculated from the direct measurement of T and N are considered to represent the yield value and viscosity of the paste or mortar tested relatively and are used for the analysis of the rheological characteristics.

### (3) Viscometer for concrete

The BML-viscometer is frequently used for research on the rheology of fresh concrete [29-33]. Figure 2.34 shows the principle of the BML-viscometer. It is a coaxial cylindrical viscometer that is able to measure the rheological properties of coarse particle suspensions like mortar and concrete. It consists of a system of inner and outer cylinders. An electric motor controls the speed of the outer cylinder, while the inner cylinder registers the torque by use of a load cell. The principle of the evaluation of the result is the same as mentioned above for a paste-viscometer.

Due to the time-consuming testing procedure and the expensive devises, the BML-viscometer is not developed to be a quality control method at the construction site. It is mostly applied for mix design on a laboratory scale.

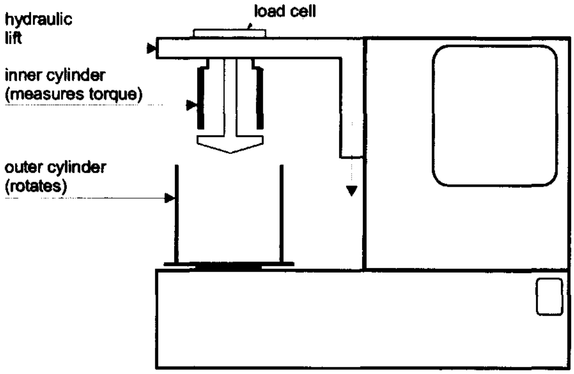


Figure 2.34 Principle of BML-viscometer [33]

## 2.4 RESEARCH ON ADMIXTURES AND MIXING RELATED TO THE PROPERTIES OF SCC

### 2.4.1 Characterization of superplasticizers

#### (1) Theories on the dispersion mechanism of superplasticizers

The effect of a superplasticizer with regard to dispersing the cement particles, which improves the fluidity of cement pastes, can be obtained by two repulsive effects: an electrostatic repulsive force and a steric hindrance effect in general [34][35]. In both effects macromolecules of the superplasticizer are expected to be adsorbed on the surface of the cement particles. Furthermore, the effect of non-adsorbed macromolecules existing in the cement suspension is supposed to be an important factor for the improvement of the fluidity [17]. *Ohta* et al. have given a good summary of the underlying theories [35][36]. The most important theories are described in the following.

### DLVO theory

The electrical repulsion mechanism can be explained by the DLVO theory (Derjaguin, Landau, Verwey and Overbeek) in which there is a correlation between the magnitude of the zeta-potential on the surface and the dispersibility of cement particles [37]. Electrical repulsion is the mechanism of dispersion of β-naphthalene sulfonate formaldehyde condensate (BNS) and melamine sulfonate formaldehyde condensate (MS) [38][39].

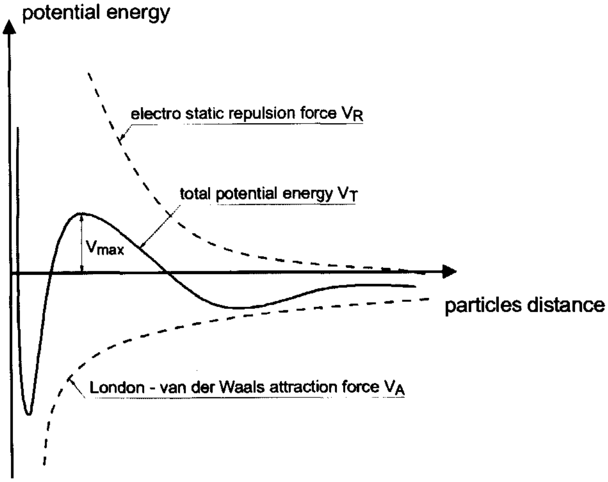


Figure 2.35 Potential energy curve in DLVO theory [36]

Dispersion stability of particles is determined based on the shape of the total potential energy ($V_T$) curves of the electrostatic repulsion force ($V_R$) obtained when two particles approach, and London-van der Waals attraction ($V_A$). When the distance between two particles corresponds to the point on the curve where $V_T$ is at the maximum ($V_{max}$), the two particles are dispersed (see Figure 2.35). As $V_{max}$ increases, the dispersibility increases and exhibits a co-relationship with that of the zeta-potential [40].

When the zeta-potential on the surface of cement particles is −20 mV, a barrier of potential energy appears between particles [38][39]. Then, particles cannot move any closer to each other and the dispersion is stable.

**Steric effect theory**

With polycarboxylate(PC)-based superplasticizers, cement particles are dispersed to obtain a water reducing effect due to two factors: 1) low electric repulsion caused by the adsorption of negative ions of the carboxylic group in the chemical structure onto the surface of a cement particle; and 2) the steric effect due to the main chain and the side chains. Therefore, PC-based water-reducing agents can obtain equal water reduction at a much smaller dosage than BNS- and MS-based dispersing agents.

In this manner, the zeta-potential on the surface of cement particles with PC-based agents is less than half of that of particles with BNS-based agents. According to the DLVO theory, the energy barrier does not appear even when the potential between particles is calculated from the static repulsion forces, and the cement particles should agglomerate.

In order to compensate the dispersion effect of PC-based superplasticizers, the steric effect theory was proposed. The dispersion stability of steric effects can be explained based on the entropy theory proposed by Mackor [41]. The total potential energy $V_T$ between two particles is given by $V_T = V_A + V_R^S$. $V_A$ is the van der Waals attractive potential energy and $V_R^S$ is the steric repulsive potential energy calculated as an entropy term from the structure and conformation of adsorbed surfactant on the particles. This theory is called the osmotic pressure effect theory by Fisher and Ottewill [42][43].

**Depletion effect theory**

The depletion effect theory was put forward by D. H. Napper et al. in 1980, and states that polymers disperse and flocculate even if they are in a free state and without adsorption [44]. Figure 2.36 shows an outline of the depletion effect [35].

If the spread of a soluble polymer is comparatively greater than the size of the dispersing particles, the space between the particles when they come into contact with each other is so small that the polymer molecules cannot occupy the spaces and depletion flocculation occurs. If an excessive dosage of polymer is added to the dispersion system and a surplus remains in the solution after adsorption saturation, this surplus polymer fills the spaces between adjacent dispersed particles, and the depletion dispersion effect is stabilized without particle flocculation [37][44].

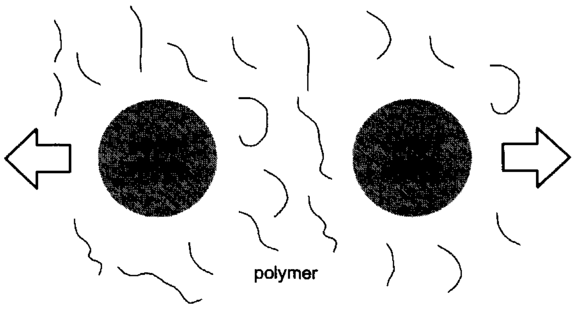


Figure 2.36 Outline of depletion effect [35]

**Tribology effect**

Tribology is the science and technology of friction, abrasion and lubrication. One example of the application of tribology in the field of mechanical engineering, in which the friction and the lubrication are of critical importance, is the addition of low-molecular weight lubricating substances which reduce the frictional resistance between particles and surfaces.

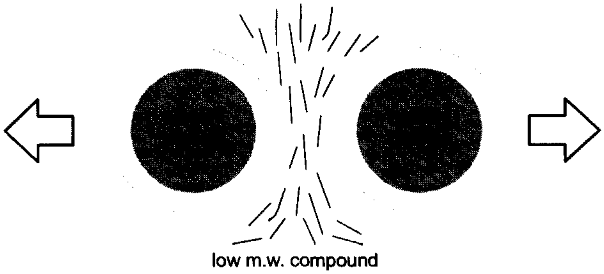


Figure 2.37 Outline of tribology effect [35]

In the field of concrete, these properties have already been introduced to admixtures. Substances with a low molecular weight give the admixture lubricating properties, reducing the frictional forces between cement particles to enhance the flowability [45] (see Figure 2.37 [35]).

The dispersion theories introduced before are the major subjects of discussion in the field of cement and additive chemistry. However, the interaction between the dispersion effect of admixtures themselves and the mixing effect is not mentioned at all in these theories.

### (2) Influence of sulfate ions on the effect of superplasticizer

According to the dispersion theories described above, "adsorption" of molecules of superplasticizer on the surface of cement (binder) particles is considered as the key behavior. *Nawa* et al. investigated the interaction between cement and superplasticizers focussing on the influence of sulfates on the adsorption behavior of a naphthalene sulfonate based superplasticizer (NFS) [46-48]. In this research, it was found that the NFS molecules adsorb rapidly and preferably onto $C_3A$ and $C_4AF$ compared to that on $C_3S$ and $C_2S$ among the composition of cement clinker. However, the adsorption of NFS onto $C_3A$ and $C_4AF$ was not effective to fluidize cement pastes and the adsorption onto $C_3S$ and $C_2S$ contributed to the fluidity of cement pastes. In this system, it was concluded that $SO_4^{2-}$ ions dissolved from sulfates existing in cement clinkers and gypsum play a role to reduce the adsorption of NFS onto $C_3A$ and $C_4AF$ and consequently increase the adsorption onto $C_3S$ and $C_2S$ that results in an increase of the fluidity of cement pastes.

Furthermore, *Kato* et al. investigated the influence of sulfate ions on the fluidity of cement paste containing a polycarboxylate-based superplasticizer (PC) [49] [50]. They made clear that an increase of the sulfate-ion concentration decreases the fluidity of cement pastes. This is the contrary tendency to the influence of sulfate ions in cement pastes containing NFS. In this case, the amount of sulfate ions did not affect so much the amount of PC molecules adsorbed onto the cement particles, and the variation of the paste flow value was not correlated with the variation of the amount of adsorption. Therefore, they concluded that the sulfate ions must decrease the thickness of the adsorption layer of PC which causes a reduction of the steric hindrance effect.

Anyhow, the amount of sulfate ions in cement paste is a governing factor for the effect of both NFS- and PC-based superplasticizers.

## 2.4.2 Studies on the effect of mixing concerning the properties of fresh concrete

### (1) General effect of mixing on the fresh properties of ordinary concrete

It is generally known that the consistency and the workability of concrete depend on the mixing conditions. *Uomoto* et al. investigated the effect of mixing, type of mixer and mixing time, on the properties of normal concrete with and without chemical admixtures [51][52]. In all cases, the slump values were increased in the initial period of mixing as a function of the increase of the electric power consumption of the mixers, and after reaching the maximum values, the slump values were reduced by the additional mixing. The mixing time necessary to reach the maximum slump value depended on the type of mixer. In general, a forced mixer required a shorter mixing time to reach the maximum slump than a gravity tilting mixer. On the other hand, it was also observed that the electric power consumption per unit concrete volume was a very effective index: a constant value of it realized a constant value of the slump regardless of the type of mixer and the mixture composition. It was concluded that 0.5 Wh/l of electric power consumption per unit concrete volume was the optimum for obtaining the maximum slump.

### (2) Effect of mixing on the fresh properties of mortar containing naphthalene sulfonate based superplasticizer

*Nawa* et al. studied experimentally in detail the influence of the mixing condition on the fluidity of low-water/cement ratio mortars containing a NFS-based superplasticizer [53] [54]. In the first series, they fixed the mixing time and varied the rotation speed of the mixer. In the case of plain mortar, the difference of the rotation speed did not significantly affect the flow value. However, an NFS-added mortar showed a smaller flow as the rotation speed increased, and it was also clarified that the amount of adsorbed NFS was increased as the rotation speed increased. This result means that a larger amount of adsorption results in a lower value of the mortar-flow. As a consequence of this phenomenon, a higher rotation speed of the mixer makes the amount of adsorbed NFS onto $C_3A$ larger, and the increase of the adsorption onto $C_3A$ consequently decreases the adsorption onto $C_3S$ that contributes to the fluidity of the mortar.

As second step was that the researchers fixed the rotation speed of the mixer and varied the mixing time. In the case of plain mortar, the flow value increased as the mixing time increased. However, the flow value of NFS-added mortar reached its maximum in the early stage of mixing and thereafter decreased monotonously as the mixing time increased. With regard to this phenomenon, it was confirmed that the amount of adsorbed NFS increased as the mixing time increased accompanying the increase of ettringite (hydration product) in the mixtures. It was observed that the increase of adsorbed NFS onto ettringite decreased the adsorption onto $C_3S$ and consequently decreased the fluidity of the mortar.

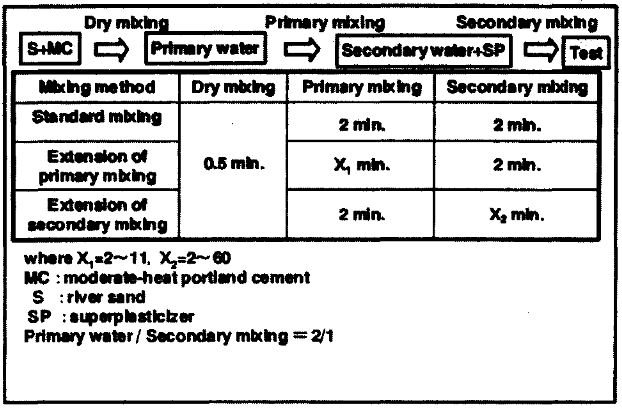
### (3) Effect of mixing on the properties of fresh mortar containing a polycarboxylate based superplasticizer

*Sugamata* selected a polycarboxylate-based superplasticizer, which is the most popular type of superplasticizer nowadays used for SCC, and studied in detail its particle dispersion effect in mortar depending on the mixing time [17] [55]. The mortars tested were composed supposing that they have sufficient self-compacting properties with an adequate amount of the coarse aggregate.

In this study, the "double mixing method" was adopted, which means that the mixing water was separated into two portions and the superplasticizer was added with the secondary water as shown in Figure 2.38. The amount of the primary water was 2/3 of the total mixing water. In some test cases, the primary mixing was extended up to 11 minutes, and in other cases the secondary mixing was extended up to 60 minutes. During and after the mixing, the following measurements were performed:

- Measurement of motor load of mixer in ampere during the mixing
- Mortar flow test (described in 2.2.9)
- Mortar funnel test(described in 2.2.9)
- Measurement of residual superplasticizer content in the liquid phase of the mortar
- Measurement of specific surface of cement particles by the BET method

In this study, the dispersion effect of the superplasticizer was evaluated by the value of $\Gamma_m$/ $R_m$, according to the method introduced by *Ouchi* (see 2.1.4).



| Mixing method | Dry mixing | Primary mixing | Secondary mixing |
|---|---|---|---|
| Standard mixing | 0.5 min. | 2 min. | 2 min. |
| Extension of primary mixing | | $X_1$ min. | 2 min. |
| Extension of secondary mixing | | 2 min. | $X_2$ min. |

where $X_1$=2~11, $X_2$=2~60
MC : moderate-heat portland cement
S : river sand
SP : superplasticizer
Primary water / Secondary mixing = 2/1

Figure 2.38 Mixing method for mortar [17]

On the basis of the experiments, *Sugamata* concluded the following:

(1) Both the extension of the primary mixing and the extension of the secondary mixing resulted in a reduction of both $\Gamma_m$ and $R_m$ (see Figure 2.39 and 2.40). In this case, the extension of the primary mixing time with the dry mixture shows a larger influence on the reduction of $\Gamma_m$ and $R_m$ than the extension of the secondary mixing time with the wet mixture.

(2) The change in fluidity due to the extended mixing time expressed by the $\Gamma_m$ - $R_m$ relationship

is approximately similar to the change in fluidity obtained by varying the superplasticizer dosage in the mixture proportions (see Figure 2.41)

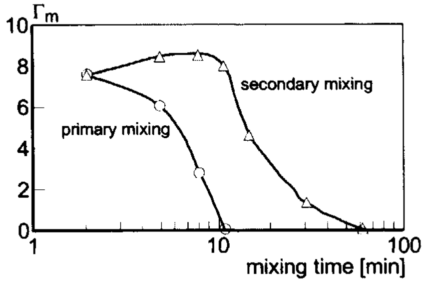


Figure 2.39 Relationship between mixing time and $\Gamma_m$ [17]

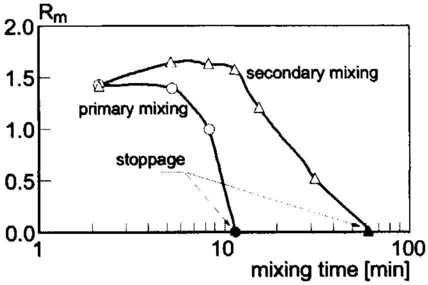


Figure 2.40 Relationship between mixing time and $R_m$ [17]

(3) The particle-dispersing effect of the superplasticizer gradually decreases as the mixing time increases and the loss in the particle-dispersing effect is greater in the mixtures for which higher power has been consumed during the same mixing time (see Figure 2.42).

(4) The amount of the superplasticizer adsorbed per unit weight of cement increases as the mixing time increases, and the increase is more evident in the mixtures which consumed more power during the mixing (see Figure 2.43). Furthermore, the particle-dispersing effect of the superplasticizer is inversely proportional to the amount of adsorbed superplasticizer per unit weight of cement (see Figure 2.44). In other words, the dispersing effect of the superplasticizer as a function of the mixing time is positively proportional to the amount of residual superplasticizer in the liquid phase per unit weight of cement (see Figure 2.45)

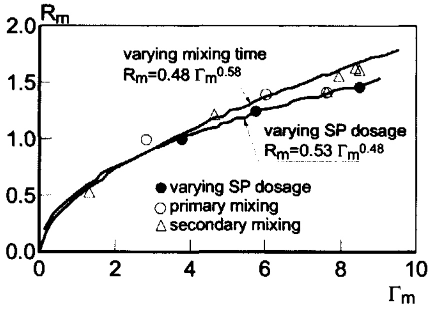


Figure 2.41 Relationship between $\Gamma_m$ and $R_m$ [17]

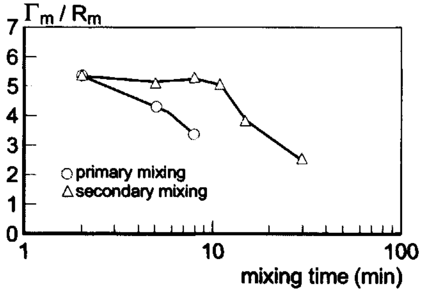


Figure 2.42 Change in $\Gamma_m/R_m$ in time [17]

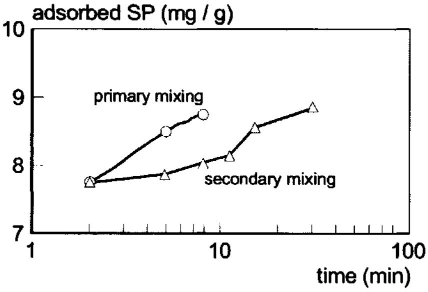


Figure 2.43 Change in amount of adsorbed SP per unit weight of cement in time [17]

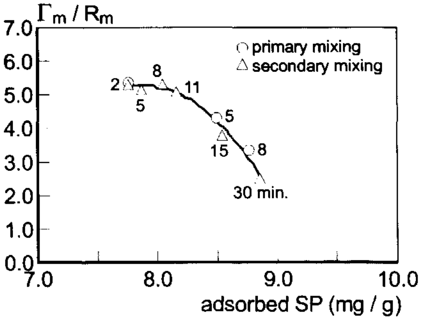


Figure 2.44 Relationship between amount of adsorbed SP and $\Gamma_m/R_m$ [17]

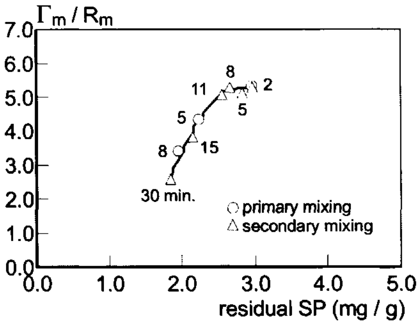


Figure 2.45 Relationship between residual SP amount and $\Gamma_m/R_m$ [17]

(5) It was demonstrated that the principal reason for the losses in the particle-dispersing effect of a superplasticizer during extended mixing is the increase of the specific surface of cement due to hydration after contact with water (see Figure 2.46). Accordingly, the amount of adsorbed superplasticizer per unit surface area of cement decreased as the mixing time increased (see Figure 2.47).

(6) By expressing the superplasticizer adsorption by the amount per unit surface area instead of the amount per unit weight, its particle-dispersing effect increases as the adsorption increases during the extended mixing similarly to the case of varying its dosage (see Figure 2.48). The particle-dispersing action of the polycarboxylate-based superplasticizer by steric hindrance is clearly exhibited in terms of mixing time as well.

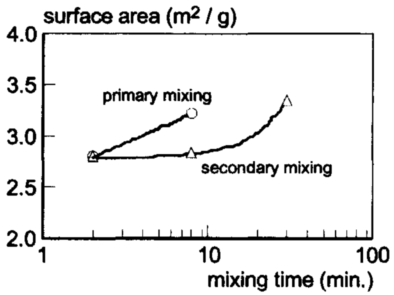


Figure 2.46 Relationship between mixing time and BET specific surface area of cement [17]

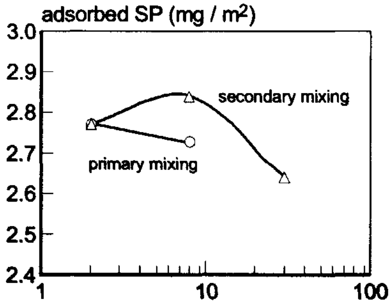


Figure 2.47 Relationship between mixing time and amount of adsorbed SP per unit surface area of cement [17]

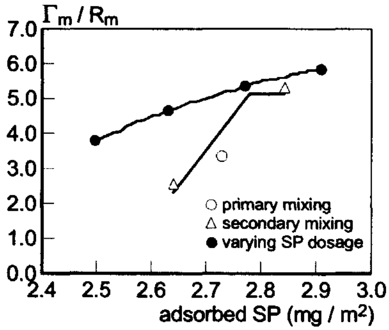


Figure 2.48 Relationship between amount of adsorbed SP per unit surface area of cement and $\Gamma_m/R_m$ [17]

### 2.4.3 Studies on the properties of welan gum as a viscosity modifying admixture for SCC

Welan gum, a kind of water-soluble natural polysaccharide, is one of the most popular viscosity modifying admixtures utilized for SCC to improve the stability of fresh concrete. It was firstly observed by *Yurugi* and *Sakata* et al. that welan gum was an effective material for the combination-type SCC [13][22]. It was also applied as an anti-washout admixture for underwater concrete [56].

Figure 2.49 shows the chemical structure of welan gum. *Sakata* et al. investigated its basic properties and effects on SCC in detail in comparison with some other viscosity agents [57] [58]. Figure 2.50 shows the viscosity of each viscosity agent's solution under various types of water comparatively. Welan gum provides almost the same viscosity independent of the water type, and it tends to give a little higher viscosity in the alkaline solution and the filtered cement water dispersions than in the de-ionized water. Moreover, the welan gum solution shows an almost constant viscosity independent of the pH. Figure 2.51 shows the relation between the percentage of the viscosity, determined at 5°C as 100%, and the temperature. It is recognized that the viscosity of welan gum solution does not vary with the temperature. Figure 2.52 shows the relation between the shear rate and the viscosity of each viscosity agent's solution. The welan gum solution's viscosity decreases sharply as the shear rate increases, which is called pseudoplastic behavior. This property is considered as the main reason that welan gum stabilizes the flowability of SCC well.

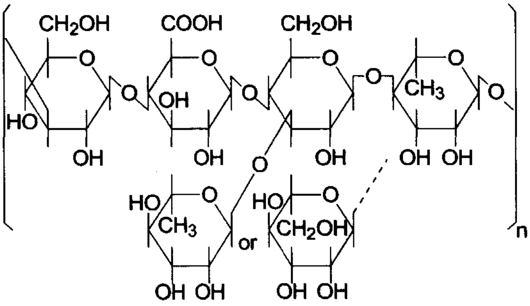


Figure 2.49 Chemical structure of welan gum [58]

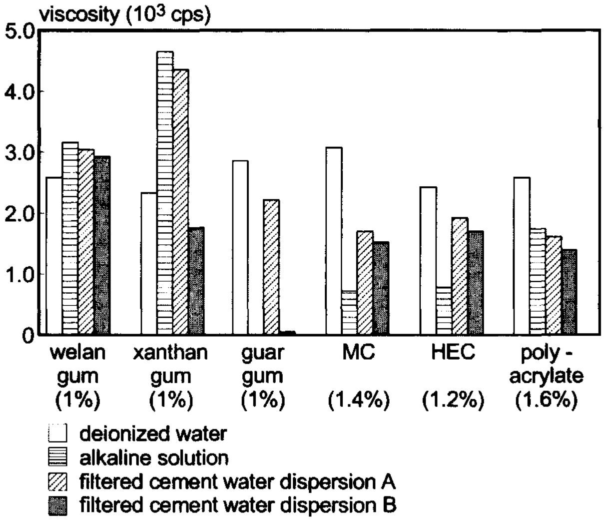


Figure 2.50 Each viscosity of viscosity agents' solution under various types of water

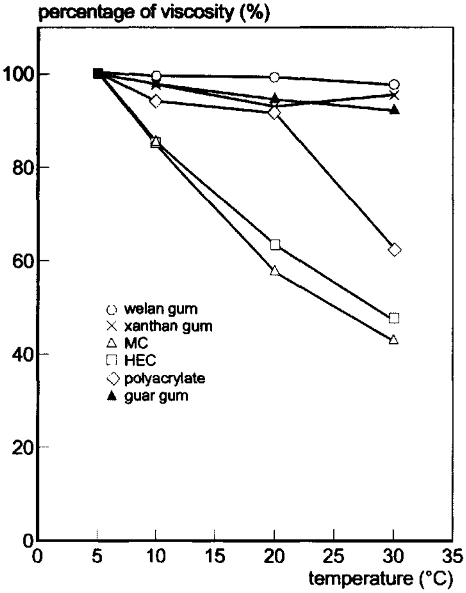


Figure 2.51 Relation between percentage of viscosity and temperature [58]

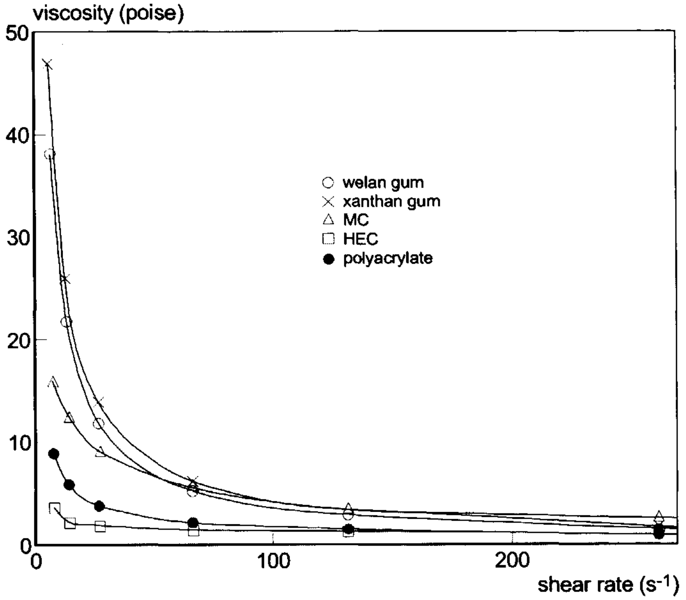


Figure 2.52 Relation between shear rate and viscosity [58]

Figure 2.53 - 2.55 show the variation of SCC properties, slump-flow value, V-funnel flow speed and U-shape filling height, depending on the variation of unit water content. The SCC mixture with welan gum shows a very high toughness against a variation of the water content and also the time passing. In this test, a naphthalene sulfonate based superplasticizer was used and SCC with welan gum needed 50% more dosage of it than a non-welan gum mixture in spite of the fact that the basic mixture proportion was fixed. According to these results, it was concluded and hypothesized that welan gum works by restraining the superplasticizer molecules and preventing them from adsorption to the cement particles, and the restrained superplasticizer contributes to the dispersion of the cement time-dependently being released from the welan gum.

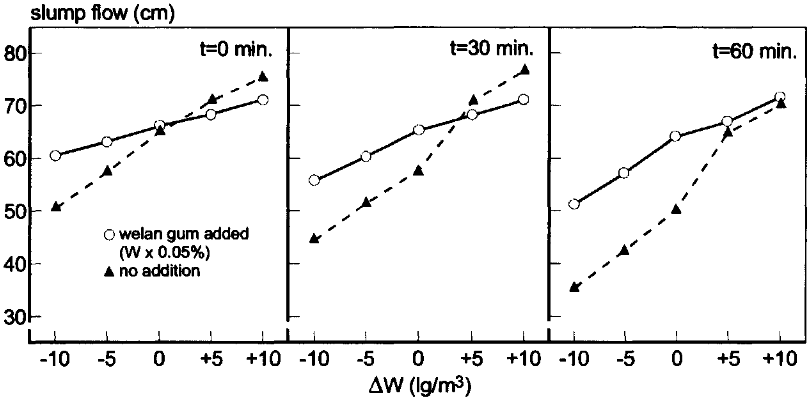


Figure 2.53 Variation of slump-flow value depending on change of unit water content [58]

a. Just after mixing

b. 30 min after mixing

c. 60 min after mixing

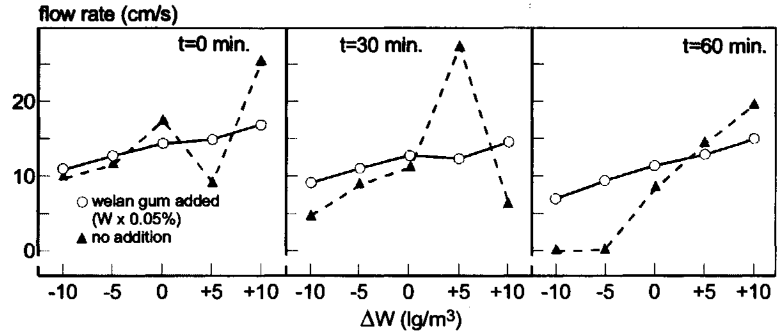


Figure 2.54 Variation of V-funnel flow rate depending on change of unit water content [58]

a. Just after mixing

b. 30 min after mixing

c. 60 min after mixing

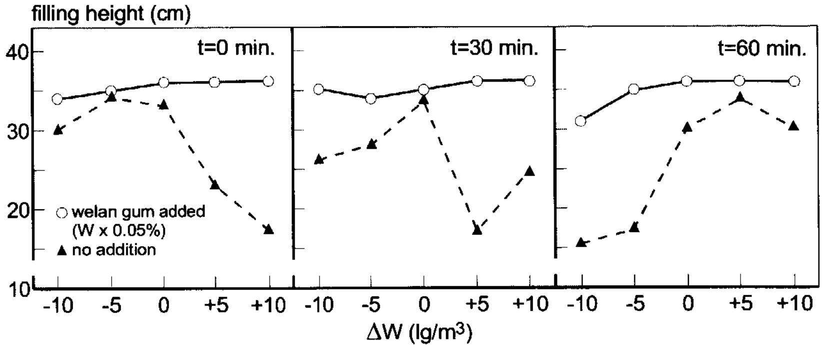


Figure 2.55 Variation of U-box filling height depending on change of unit water content [58]

a. Just after mixing
b. 30 min after mixing
c. 60 min after mixing

# CHAPTER 3
# DEVELOPMENT OF SCC IN THE NETHERLANDS

## 3.1 INTRODUCTION

Application of self-compacting concrete makes the quality assurance of concrete structures independent of the skill of laborers. Furthermore, it gives many advantages for the concrete construction practice, e.g. a reduction of the construction cost and period, an improvement of the working conditions by virtue of less noise and vibration, and an increase of the freedom in structural design.

SCC was developed in Japan and has been successfully applied to many structures in the last decade. However, it was hardly used in Europe in spite of its recognized usefulness when the author started his guest researchership at the Delft University of Technology in 1996. Therefore, the author started investigating the producibility of SCC in the Netherlands, in the spring of 1997. In this chapter, the process of the development of SCC in the Netherlands is described in detail.

## 3.2 APPLIED MIX DESIGN SYSTEM OF SCC

### 3.2.1 Mix design philosophy

The fundamental concept of realizing self-compactability of fresh concrete was described in detail in 2.2.2. There are numerous solutions to realize self-compactability. For example, the target level of self-compactability depends on the type of structure where SCC is applied. Slabs and walls require a different priority for concrete between the levelling ability and the pass-through ability. If SCC is applied to a dam, deformability is considered to be the main feature of the concrete because of little reinforcement. If SCC is applied to a seismic designed structure, the segregation resistance between the coarse aggregate and the mortar is very important as well as the deformability due to the heavily arranged reinforcement. Moreover, if other properties of concrete, e.g. heat of hydration, shrinkage resistance, cost etc., are more important than the compactability of fresh concrete, the mix design might be done in different ways.

Furthermore, the mix design system for SCC depends on the materials used. In Japan, SCC is mainly categorized in the following three types according to the method used for obtaining adequate viscosity of the paste in concrete: (a) powder type, (b) viscosity agent type and (c) combination type [59]. The combination type is similar to the powder type but a viscosity agent is used to assist gaining adequate viscosity and to make the concrete stable against fluctuation of material characteristics. Of course, each type of SCC is recommended to be designed in a different way.

Actually, there are many design philosophies for SCC in Japan and mixture proportioning is usually taylored to the structure considered. In one case, the coarse aggregate volume may be 330 l/m$^3$. In another case, only 280 l/m$^3$ of coarse aggregate may be used. This depends on the filling-difficulty for the concrete, regarding the geometry and the reinforcement congestion in the structure. It furthermore depends on the quality of the aggregate. For some cases the fine aggregate volume is designed as 43 % of the mortar volume, but for other cases it is only 38 %. It sometimes depends on the required self-levelling ability for a long distance, and sometimes depends on the pressure-transmitting ability for casting in a closed space. The slump flow value is generally targeted at 650 mm, but 750 mm is sometimes required as well. Then, the water-powder ratio is adjusted to give the concrete an adequate segregation resistance. An SCC mixture designer must consider the geometrical characteristics of the structure in order to determine the required properties of the concrete, and he should know the characteristics of the materials applied, and should design a mixture fulfilling the required properties in the most economical way. Furthermore, the concrete should be durable for its life.

As described before, there is a unique mixture designing philosophy for each construction project and each structure in general. Only experienced SCC mixture designers can deal with many different circumstances and such designers always know the basic principles of the design of SCC. In other words, an engineer who knows only a unique SCC mixture for a particular structure cannot by definition design a proper mixture for a totally different type of structure. Many concrete engineers tend to take the shortest route to obtain an adequate mixture for a particular structure without understanding the basic principle. Such engineers cannot master other cases and often make mistakes. Therefore, it is important for "beginners" to learn an orthodox designing method that helps to let them understand the basic principle. From this point of view, the SCC mixture design system recommended by *Okamura et al.*, the so called "general purpose approach", is introduced and applied in this project.

The design system of the general purpose approach aims at achieving a high-level self-compactability of the fresh concrete and at obtaining adequate properties of the hardening and the hardened concrete implicitly. An SCC mixture designed according to the system is directly applicable to various types of structures. Therefore, it is a useful method for an unexperienced designer. In other words, the mixture is sometimes not the most rational solution for a particular type of structure. In such a case, an experienced designer may modify it if he understands the basic principle well. Figure 3.1 shows the position of the general purpose approach in the mixture design philosophy of SCC.

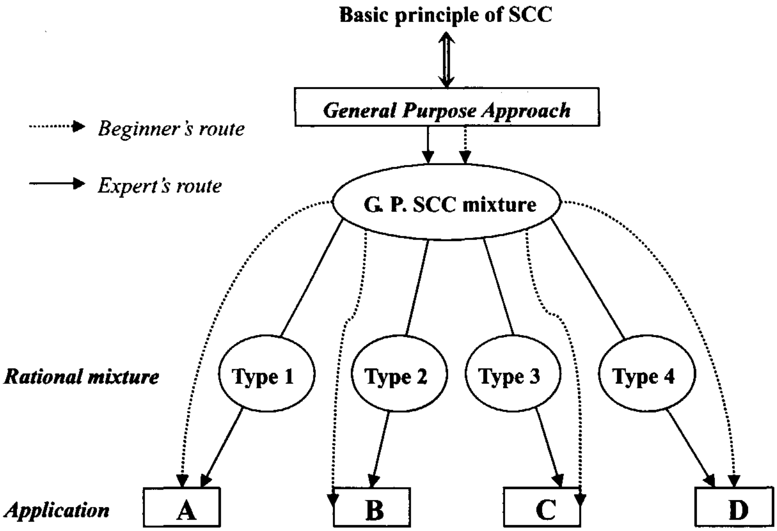


Figure 3.1 Position of general purpose approach

The general purpose approach is originally intended to be applied to the "powder type" SCC. However, in this research, the design system was considered to be applicable also to the "combination type" which employs welan gum as a viscosity modifying admixture.

### 3.2.2 General purpose approach

As described in 2.2.3, the mix proportion of SCC according to the general purpose approach is designed in the following steps: determination of (a) air content, (b) coarse aggregate volume, (c) fine aggregate volume, (d) water to powder volume ratio (e) superplasticizer dosage. The air content "A" is determined at an adequate value considering the resistance to freezing-and-thawing. The coarse aggregate volume "G" is determined at 50% of its solid volume in the concrete volume except the air.

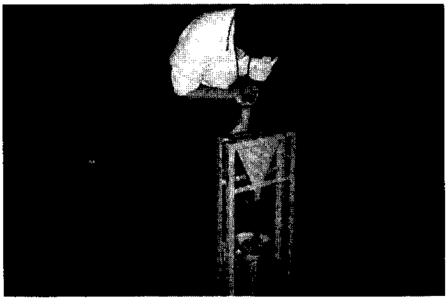
$G = 0.5G_{\text{lim}}(1 - A)$ $G_{\text{lim}}$ : solid volume ratio of coarse aggregate

The fine aggregate volume "S" is determined at 40% of the mortar volume, where the particles finer than 0.09 mm are not considered as aggregate, but as powder.

$S = \dfrac{0.4(1 - A - G)}{1 - \kappa_{sf}}$ $\kappa_{sf}$ : fine particle(<0.09 mm) ratio in fine aggregate

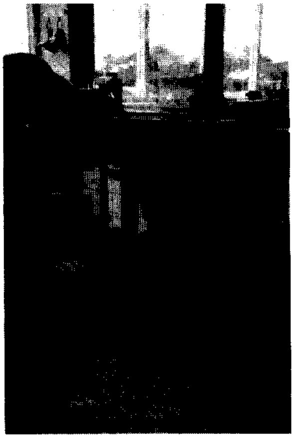
The water to powder volume ratio "$V_w/V_p$" has to be determined by tests on mortar, because it is strongly influenced by physical and chemical properties of the applied powder, chemical admixture and fine aggregate. To estimate the ratio $V_w/V_p$, the mortar flow test and the mortar funnel test are executed (see 2.2.9). Pictures 3.1 and 3.2 show the conditions of the tests. The fine aggregate (>0.09 mm) volume in the mortar is 40% as mentioned above. The adequate value for $V_w/V_p$ is estimated to realize the relative flow area $\Gamma_m=5$ and the relative funnel speed $R_m=1$ simultaneously with the effect of the superplasticizer.

Picture 3.1 Mortar flow test



Picture 3.2 Mortar funnel test

The dosage of superplasticizer Sp/P (% of powder weight) is roughly estimated by the mortar test mentioned above. However, the effect of the superplasticizer in the concrete is possibly different from the effect in the mortar due to the difference in the mixing efficiency. Therefore, the adequate dosage of superplasticizer has to be estimated by the concrete test. To estimate Sp/P, the concrete slump flow test is executed. At this stage, the mix proportion of concrete, except the dosage of superplasticizer, is already designed by the values of A, G, S and $V_w/V_p$. The proper Sp/P is estimated to realize 650±50 mm of the slump flow. Furthermore, another concrete test is recommended to evaluate the property of SCC. Figure 2.18 (see 2.3.3) and Picture 3.3 show the test apparatus of V funnel test. A properly designed SCC according to the explained process should result in a relative funnel speed $R_c$ between 0.5 and 1.0.



Picture 3.3 V funnel test

The mix design method according to the general purpose approach explained above aimed to popularize SCC widely in Japan considering the materials available in the Japanese market. Therefore, there are some premises to apply this method:

(a) The maximum size of the aggregate is 20 mm.
(b) The border size between fine and coarse aggregate is 5mm (Japanese standard).
(c) Japanese moderate heat Portland cement is used as a standard powder material.
(d) A forced mixer, pan type or pugmill type, is used to produce SCC.

## 3.3 CHARACTERISTICS OF APPLIED DUTCH MATERIALS

### 3.3.1 Powder materials (cement and mineral admixtures)

Table 3.1 shows the characteristics of the applied powder materials. All of them are available on the Dutch market and most of them are commonly used in the Dutch ready-mixed concrete industry. Blast furnace slag cement (BSC)-A1 and A2 are from the same brand, but the delivery dates are different. BSC-B is finer than BSC-A. The limestone powder (LS) is a product from Germany. Fly ash cement (FAC) and fly ash (FA) are of the type commonly used in the Netherlands.

Table 3.1 Characteristics of powder materials

| Powder name | Specific gravity | Blaine ($m^2/kg$) | Clinker (%) | Slag (%) | Fly ash (%) | CaO (%) |
|---|---|---|---|---|---|---|
| Blast furnace slag cement (BSC) A1 | 2.94 | 403 | 22.6 | 70.1 | 2.4 | 41.1 |
| Blast furnace slag cement (BSC) A2 | 2.94 | 381 | 21.8 | 70.3 | 3.3 | 41.8 |
| Blast furnace slag cement (BSC) B | 2.98 | 526 | 23.0 | 71.0 | - | 45.9 |
| Flyash cement (FAC) | 2.89 | 426 | 67.0 | - | 27.0 | 47.3 |
| Limestone powder (LS) | 2.73 | 303 | - | - | - | 55.0 |
| Fly ash (FA) | 2.33 | 277 | - | - | 100 | - |

### 3.3.2 Chemical admixtures

Table 3.2 shows the characteristics of the applied superplasticizers. SP-A, B, C and D are available in the Dutch market and SP-E is a Japanese product which was tested as a reference. SP-B has a similar active polymer as SP-A, but the initial dispersibility is lower than for A.

However, SP-B has a better ability of slump retention. SP-C and D have been used in the Netherlands for a long time.

Table 3.2 Characteristics of superplasticizers

| | Product name | Chemical description | Specific gravity* |
|---|---|---|---|
| SP-A | Glenium 51 | Polycarboxylic ether complex | 1.10 |
| SP-B | Glenium 27 | Polycarboxylic ether complex | 1.05 |
| SP-C | Rheobuild 2000 PF | Naphthalene sulfonate and melamine sulfonate | 1.23 |
| SP-D | Betomix 415+O | Naphthalene sulfonate | 1.21 |
| SP-E | Rheobuild SP-8HS | Complex of polycarboxylic ether and cross-linked polymer | 1.05 |

*solution base

Welan gum was used as a viscosity modifying admixture in this research. So far, it has been used for concrete in Japan and North America, mainly. The welan gum used in this research was imported from USA via Japan. It is available also in the European market because it is produced in UK.

### 3.3.3 Aggregate

The characteristics of the fine and the coarse aggregate used are shown in Table 3.3. A sufficient amount of aggregate for this research program was sampled from a ready-mixed concrete plant at once. These are typical Dutch river sands and river gravels with a round shape. The maximum size of the gravel is 16mm. The border size between fine and coarse aggregate, the maximum size of the sand, is 4mm in the Dutch standard.

Table 3.3 Characteristics of aggregate

| | type | Specific gravity* | Absorption (%) | F.M. | $\kappa_{sf}$ (<0.125mm) | Solid volume |
|---|---|---|---|---|---|---|
| Fine aggregate | River sand (0-4mm) | 2.60 | 0.90 | 2.98 | 0.6% | - |
| Coarse aggregate | River gravel (4-16mm) | 2.53 | 1.54 | 6.54 | - | 66.0% |

* saturated surface dry base

## 3.4 EXPERIMENTAL PROGRAM

### 3.4.1 Premises to apply the general purpose approach

As the design system explained above is applied to Dutch materials, the following premises are considered:

(a) The influence of the difference between the Japanese standard and the Dutch standard concerning the maximum size of the fine aggregate is practically negligible.

(b) Fine particles (<0.125mm) in the fine aggregate are considered as a part of the powder because of the sieve size according to the Dutch standard.

(c) The mortar, which includes 40% of the fine aggregate and realizes $\Gamma_m$=5 and $R_m$=1 simultaneously, is suitable for SCC even when arbitrary kinds of powder materials are used.

The reason why the above premises were adopted is to develop the prototype of Dutch SCC as early as possible. Therefore, it was not aimed in this study to modify the mixture design method and the testing methods to make them be more suitable for the Dutch conditions. Of course, the difference between the Japanese and the Dutch materials could be considered to be sufficiently small and the general purpose approach with the mentioned premises was considered to be the best starting point for this research.

Furthermore, in the following experimental program, it was aimed at finding a materials combination and a mixture proportion to realize the self-compactability of fresh concrete. At this stage, the strength level of the hardened concrete was not focussed and it was considered as a resulting characteristic of the obtained mixture.

### 3.4.2 Paste test

In order to determine the properties of the powder composition used, the paste flow test was executed firstly. Table 3.4 shows the applied powder compositions. For any composition, the water retaining ratio "$\beta_p$" and the deformation factor "$E_p$" were estimated for plain paste according to the following procedure.

Table 3.4 Tested powder compositions

| powder composition (% in volume) |
|---|
| BSC-A1 100% |
| BSC-A2 100% |
| BSC-B 100% |
| FAC 100% |
| LS 100% |
| FA 100% |
| BSC-A1 50% + LS 50% |
| BSC-A1 75% + LS 25% |
| FAC 50% + LS 50% |
| BSC-A1 75% + FA 25% |
| BSC-A2 60% + FA 40% |

(a) Three pastes were mixed with different values of $V_w/V_p$, e.g. 1.0, 1.1 and 1.2, and the spread diameter of the flow test was measured (see Figure 2.30). Three values of $V_w/V_p$ were chosen to make the $\Gamma_p$ result generally between 1.0 and 4.0. Flow tests were executed twice and the average value was taken as the test result.

(b) 1-liter of paste was mixed by a Hobart mixer (model N-50, 2-liter capacity) and the mixing time was four minutes totally. During the first minute, all of the powder and the first water ($W_1$) were mixed at a low rotation speed. Then, the paste stuck on the wall of the mixer pot was scratched. During the second minute, the paste was mixed at a high rotation speed. During the third minute, the paste was mixed with the second part of the water ($W_2$) at a low rotation speed. Then, the paste stuck on the wall of the mixer pot was scratched again. During the fourth minute, the paste was mixed at a low rotation speed. $V_{w1}/V_p$ was determined around 0.8 to make the mixing condition during the first and second minute comparable for each powder composition.

(c) After the mixing, the paste flow test was conducted without any shaking of the table and the flow diameters were measured as shown in Figure 2.30. The flow test was executed two times in sequence and the relative flow area of the paste, $\Gamma_p$, was determined using the average value of the testing data. $V_w/V_p$ and the corresponding $\Gamma_p$ were plotted on a graph and a regression line was drawn. Then, $\beta_p$ and $E_p$ were estimated as shown in Figure 3.2. The $\beta_p$ is the water to powder volume ratio when the deformation of the paste is zero and the void among the powder particles is saturated with the water.

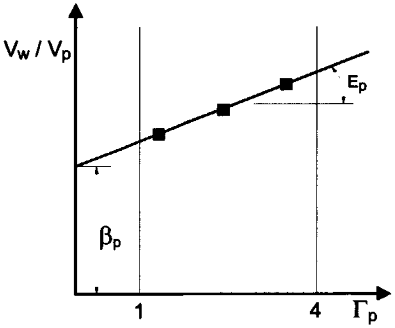


Figure 3.2 Estimation of powder characteristics

### 3.4.3 Mortar test

The adequate ratio $V_w/V_p$, which realizes $\Gamma_m$=5 and $R_m$=1 simultaneously, was estimated for each combination of powder composition and superplasticizer. The volume fraction of fine aggregate (>0.125mm) in mortar, $S_c/M$, was fixed at 40%. 21 combinations, shown in Table 3.5, were tested. 2-liter of mortar was mixed by a Hobart mixer (5-liter capacity) and the mixing time was four minutes totally. The mixing procedure is as follows : (a) During the first minute, all the powder (also the welan gum) and $W_1$ were mixed at a low rotation speed. $V_{w1}/V_p$ was then determined as 0.7 times $\beta_p$ of the powder composition used. (b) The mortar stuck on the wall of the mixer pot was scratched and mixed for another minute at a low rotation speed. (c) During the third minute, the mortar was mixed with $W_2$(=W-$W_1$) and the superplasticizer at a low rotation speed. (d) The mortar stuck on the wall of the mixer pot was scratched and mixed for another minute at a low rotation speed.

When using SP-B, the mixing procedure was slightly changed because its initial dispersibility is weak and the flowability of the mortar possibly increases after mixing. Therefore, the following procedure was adopted for mortars including SP-B instead of above (d) : (d') The mortar stuck on the wall of the mixer pot was scratched and mixed for another half a minute at a low rotation speed. Then, the mortar was left in the mixer pot statically for one minute. After one minute of rest, the mixer was restarted and the mortar was mixed for another half a minute at a low rotation speed.

For the mortar test, the sand was controlled at saturated surface dry condition.

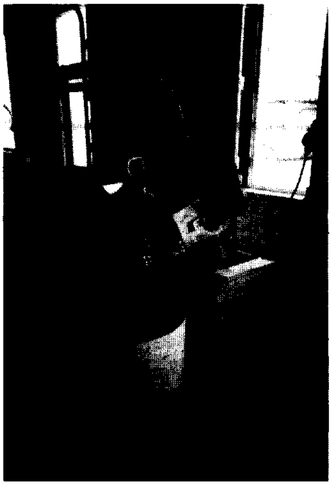
Table 3.5 Tested material combinations in mortar test

| powder composition (% in volume) | Superplasticizer | welan gum |
|---|---|---|
| BSC-A1 100% | SP-A | - |
| BSC-A1 100% | SP-B | - |
| BSC-A1 100% | SP-C | - |
| BSC-A1 100% | SP-D | - |
| BSC-A1 100% | SP-E | - |
| BSC-A1 100% | SP-B | 0.05%* |
| BSC-A1 100% | SP-E | 0.05%* |
| BSC-B 100% | SP-A | - |
| FAC 100% | SP-A | - |
| FAC 100% | SP-D | - |
| FAC 100% | SP-E | - |
| BSC-A1 50% + LS 50% | SP-B | - |
| BSC-A1 50% + LS 50% | SP-E | - |
| BSC-A1 75% + LS 25% | SP-B | - |
| BSC-A1 75% + LS 25% | SP-B | 0.05%* |
| FAC 50% + LS 50% | SP-D | - |
| BSC-A1 75% + FA 25% | SP-B | - |
| BSC-A1 75% + FA 25% | SP-B | 0.05%* |
| BSC-A2 60% + FA 40% | SP-A&B(1:2.5) | - |
| BSC-A2 60% + FA 40% | SP-A&B(1:2.5) | 0.05%* |
| BSC-A2 100% | SP-A&B(1:2.5) | - |

* percentage to water content

### 3.4.4 Concrete test

In order to estimate the adequate Sp/P and confirm the self-compactability of the designed concrete, some concrete tests were carried out. Picture 3.4 shows the forced pan mixer used. The mixer had four rotatable-paddles on a shaft and two fixed paddles. The inner diameter of the pan was 700 mm. The shaft of the rotatable-paddle turned at 83 rpm. The pan also turned in the same direction with the shaft at 27 rpm where the fixed paddles performed a backspin effect. The mixing capacity of the mixer was 50 liters. 45-liter concrete was mixed by this mixer for 1 batch.



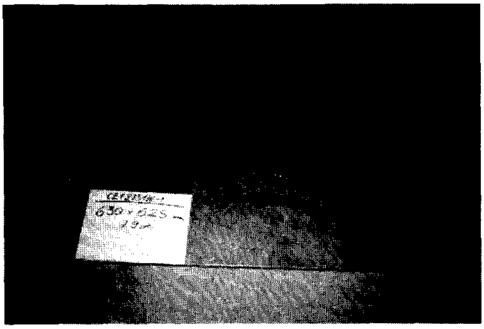
Picture 3.4 Forced pan mixer

The mixing procedure applied was as follows: (a) The sand and the powder materials (also the welan gum) were added to the mixer and the mixer was started. (b) The water and the superplasticizer were added to the mixer after 10-seconds dry mixing during the next 20 seconds. (c) The mixer was stopped 2 minutes after starting. (d) The gravel was added to the mixer and the concrete was mixed for another 1.5 minutes. The total mixing time was 3.5 minutes.

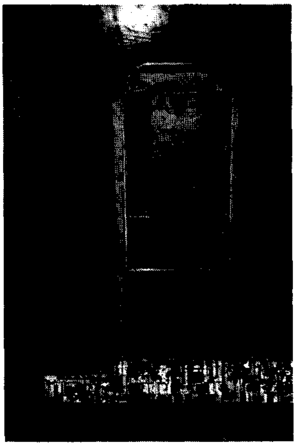
When using SP-B, the following procedure was adopted: instead of (d) above, (d') is used. The gravel was added to the mixer and the concrete was mixed for 1 minute. Then the concrete was left in the mixer statically for one minute, the mixer was restarted and the concrete was mixed for another half a minute.
For the concrete test, the sand and the gravel were controlled at wet condition, the moisture content was around 2%, and the amount of mixing water was adjusted by the surface moisture of the aggregate.

Two batches of concrete were mixed in sequence and they were put together. So, the total amount of concrete mixed was 90 liters for each mixture. For all mixtures, the slump flow test and the V funnel test were executed. Sp/P was adjusted until the slump flow resulted in 650±50mm (see Picture 3.5). When the target slump flow was obtained, the box-shaped self-compactability test (see 2.3.6 and Picture 3.6) [59], the filling vessel test (see Figure 2.21)

[22] and the time dependent slump flow test were conducted. In this investigation, the following properties are considered as required for the general purpose SCC : (a) The filling height of the box is more than 300mm. (b) The filling ratio of the filling vessel test, F, is more than 90%. (c) The target slump flow is retained for 1 hour at least.



Picture 3.5 Example of slump flow



Picture 3.6 Box test apparatus

From the result of the preliminary mixing test, the $V_w/V_p$ obtained by the mortar test was too low for the applied mixer and mixing procedure, because the produced concrete was very viscous and handling was heavier than expected for a proper SCC. Therefore, in this series of tests, 1.05 times the $V_w/V_p$ obtained by the mortar test was applied to each mixture, except to mixtures No.17 and 18. This point will be discussed in the following chapter.

## 3.5 RESULTS AND DISCUSSION

### 3.5.1 Overview of the test results

Table 3.6 shows the results of the paste tests. The fly ash and the limestone powder have a smaller $\beta_p$ and $E_p$ than the cements. This means that the fly ash and the limestone powder paste can deform with a smaller amount of water and the variation of $V_w/V_p$ results in a larger change of $\Gamma_p$ than in the case of the cement paste.

Table 3.6 Powder composition and results of paste test

| powder composition (% in volume) | βp | Ep |
|---|---|---|
| BSC-A1 100% | 0.951 | 0.0900 |
| BSC-A2 100% | 0.924 | 0.0870 |
| BSC-B 100% | 1.080 | 0.1180 |
| FAC 100% | 0.970 | 0.1300 |
| LS 100% | 0.757 | 0.0565 |
| FA 100% | 0.726 | 0.0435 |
| BSC-A1 50% + LS 50% | 0.870 | 0.0641 |
| BSC-A1 75% + LS 25% | 0.900 | 0.0763 |
| FAC 50% + LS 50% | 0.862 | 0.0827 |
| BSC-A1 75% + FA 25% | 0.897 | 0.0670 |
| BSC-A2 60% + FA 40% | 0.864 | 0.0623 |

Table 3.7 shows the results of the mortar tests. The adequate ratio $V_w/V_p$, which realizes $\Gamma_m=5$ and $R_m=1$ simultaneously, varies due to the combination of a powder composition and a superplasticizer. Powder which has a lower $\beta_p$ results in a lower $V_w/V_p$. The polycarboxylic ether superplasticizers show a lower $V_w/V_p$ than naphthalene and melamine types. The welan gum raises the $V_w/V_p$ comparing to the mortars without welan gum. The flowability retention is examined by mortars of the target property. The results are also shown in Table 3.7. The remarks in brackets are not verified exactly, but concluded by observation.

Table 3.7 Result of mortar tests

| powder composition (% in volume) | Superplasticizer | welan gum | adequate Vw/Vp | flow retention for 1 hour |
|---|---|---|---|---|
| BSC-A1 100% | SP-A | - | 0.745 | (NG) |
| BSC-A1 100% | SP-B | - | 0.810 | OK |
| BSC-A1 100% | SP-C | - | 0.835 | (NG) |
| BSC-A1 100% | SP-D | - | 0.815 | (NG) |
| BSC-A1 100% | SP-E | - | 0.750 | OK |
| BSC-A1 100% | SP-B | 0.05%* | 0.850 | (OK) |
| BSC-A1 100% | SP-E | 0.05%* | 0.825 | OK |
| BSC-B 100% | SP-A | - | 0.795 | NG |
| FAC 100% | SP-A | - | 0.755 | (NG) |
| FAC 100% | SP-D | - | 0.795 | NG |
| FAC 100% | SP-E | - | 0.760 | NG |
| BSC-A1 50% + LS 50% | SP-B | - | 0.765 | NG |
| BSC-A1 50% + LS 50% | SP-E | - | 0.760 | NG |
| BSC-A1 75% + LS 25% | SP-B | - | 0.795 | OK |
| BSC-A1 75% + LS 25% | SP-B | 0.05%* | 0.820 | OK |
| FAC 50% + LS 50% | SP-D | - | 0.750 | NG |
| BSC-A1 75% + FA 25% | SP-B | - | 0.770 | OK |
| BSC-A1 75% + FA 25% | SP-B | 0.05%* | 0.810 | (OK) |
| BSC-A2 60% + FA 40% | SP-A&B(1:2.5) | - | 0.765 | OK |
| BSC-A2 60% + FA 40% | SP-A&B(1:2.5) | 0.05%* | 0.790 | OK |
| BSC-A2 100% | SP-A&B(1:2.5) | - | 0.800 | (OK) |

* percentage to water content

Table 3.8 shows the results of the concrete tests. The grayed cells indicate the results which did not fulfill the requirements considered in 3.4.4. However, this does not mean that the mixtures in the grayed cells are not self-compacting concretes. Most mixtures tested were highly self-compactable during the first particular minutes after mixing. However, some mixtures had a problem on the flowability retention that resulted in a worse behaviour in the filling vessel, because the filling vessel test was carried out after the other tests, and at that time 20-30 minutes had already passed since the mixing completion.

### 3.5.2 Influence of superplasticizers on the flowability retention

Five kinds of superplasticizers were tested with the same cement among the mixtures No.1-5 (see Table 3.8). Only the mixtures with SP-B and E could fulfill all the requirements. Other ones had a problem with the flowability retention. SP-E is a Japanese superplasticizer which has a strong dispersibility and a long flowability retention. It is one of the most popular superplasticizers for SCC in Japan. SP-B consists of a similar polymer with SP-E, but the initial dispersibility is weaker than SP-A and E. From this result, SP-B is the only one which shows a good performance on the flowability retention among the superplasticizers used and available on the Dutch market.

### 3.5.3 Influence of coarse aggregate volume on self-compactability

According to the general purpose approach recommended by *Okamura et al.*[8], the amount of coarse aggregate is considered to be adequate at 50% of its solid volume ($G/G_{lim}$=50%) in order to design the self-compactability surely and safely. However, this value intends to be applied to aggregate whose maximum size is 20 mm. In this investigation, the maximum size of the aggregate is 16 mm. Therefore, a larger ratio $G/G_{lim}$ is possibly applicable to design SCC surely and safely for the same boundary condition.

With the mixtures No.6-8 and 13-15, the influence of the amount of coarse aggregate is considered (see Table 3.8). The mixtures with the $G/G_{lim}$ of 50, 55 and 60% were well compacted in the filling vessel when the mortar was properly designed. For $G/G_{lim}$=65%, it was difficult to obtain a slump flow of more than 600 mm because of the interaction of aggregate particles and also the relative funnel speed resulted in a very small value. In this case, the results of the box test and the filling vessel test did not fulfill the requirements. However, the concrete flow was not completely blocked by aggregate interlocking.

The relative funnel speed of the V funnel test varies also by the size and the amount of the coarse aggregate. When using 4-16 mm coarse aggregate, $R_c(t)$=1.0(10sec.), 0.91(11sec.), 0.77(13sec.) and 0.67(15sec.) are roughly adequate for $G/G_{lim}$=50, 55, 58 and 60%, respectively.

For properties of hardening and hardened concrete, more coarse aggregate results in better performance, generally. From the results discussed above, the adequate value of $G/G_{lim}$ to design SCC surely and safely is expected to be found between 55 and 60% when using 4-16mm coarse aggregate.

### 3.5.4 Applicability of limestone powder and fly ash for SCC

For the powder type and the combination type of SCC, 500-600 kg/m$^3$ of powder material is required to design SCC generally. Therefore, the problem of thermal stresses due to the heat of

# Table 3.8 Result of concrete test

| mix No. | Powder composition (% in volume) | Super-plasticizer | welan gum | G/Glim (%) | Sc/M (%) | Vw/Vp | SP/P (%) | slump flow (mm) | V funnel t(s) | V funnel $R_c$ | Box test $B_h$ (mm) | Filling vessel h(mm) | Filling vessel F(%) | slump flow after test (cm) | flow retention for 1 hour | $f_c$ at 28 days (N/mm$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | BSC-A1 100% | SP-A | - | 50 | 40 | 0.784 | 0.360 | 700.0 | 11.7 | 0.86 | 330 | 25 | 95.2 | 62.75 |  | 73.6 |
| 2 | BSC-A1 100% | SP-B | - | 50 | 40 | 0.849 | 0.920 | 650.0( - ) | 9.3 | 1.08 | 330 | 6 | 98.8 | 70.00 | OK | 69.5 |
| 3 | BSC-A1 100% | SP-C | - | 50 | 40 | 0.879 | 1.200 | 630.0 | 8.5 | 1.18 | 320 |  |  |  |  | 58.4 |
| 4 | BSC-A1 100% | SP-D | - | 50 | 40 | 0.855 | 1.150 | 632.5 | 9.9 | 1.01 | 336 |  |  |  |  | 64.2 |
| 5 | BSC-A1 100% | SP-E | - | 50 | 40 | 0.789 | 0.950 | 682.5 | 10.4 | 0.96 | 330 | 23 | 95.7 | 68.75 | (OK) | 66.9 |
| 6 | BSC-A1 100% | SP-B | 0.05 | 50 | 40 | 0.895 | 0.850 | 595.0( - ) | 8.7 | 1.15 | 324 | 26 | 94.9 | 67.00 | OK | 68.2 |
| 7 | BSC-A1 100% | SP-B | 0.05 | 55 | 40 | 0.895 | 0.860 | 552.5(640.0) | 10.8 | 0.93 | 323 | 37 | 92.9 | 64.50 | OK | 65.2 |
| 8 | BSC-A1 100% | SP-B | 0.05 | 60 | 40 | 0.895 | 0.890 | 565.0(635.0) | 11.1 | 0.90 | 322 | 29 | 94.2 | 66.75 | OK | 66.3 |
| 9 | FAC 100% | SP-D | - | 50 | 40 | 0.835 | 1.700 | 677.5 | 8.9 | 1.12 | 333 | 17 | 96.7 | 65.50 |  | 79.8 |
| 10 | FAC 100% | SP-E | - | 50 | 40 | 0.799 | 2.300 | 617.5 | 8.9 | 1.12 | 321 |  |  | 61.50 | OK | 85.9 |
| 11 | BSC-A1 50% + LS 50% | SP-E | - | 50 | 40 | 0.797 | 0.570 | 622.5 | 11.5 | 0.87 | 322 | 59 |  |  |  | 48.5 |
| 12 | BSC-A1 75% + LS 25% | SP-B | 0.05 | 50 | 40 | 0.861 | 0.720 | 555.0(625.0) | 12.0 | 0.84 | 325 | 46 | 91.4 | 63.00 | OK | 61.2 |
| 13 | BSC-A1 75% + FA 25% | SP-B | 0.05 | 50 | 40 | 0.851 | 0.850 | 620.0( - ) | 10.7 | 0.94 | 325 | 26 | 95.1 | 71.25 | OK | 61.2 |
| 14 | BSC-A1 75% + FA 25% | SP-B | 0.05 | 60 | 40 | 0.851 | 0.870 | 567.5( - ) | 14.9 | 0.67 | 324 | 34 | 93.2 | 66.00 | OK | 60.7 |
| 15 | BSC-A1 75% + FA 25% | SP-B | 0.05 | 65 | 40 | 0.851 | 0.890 | 520.0(570.0) | 30.3 | 0.33 |  |  |  | 59.75 | - | 59.3 |
| 16 | BSC-A2 60% + FA 40% | SP-A&B (1:2.5) | - | 55 | 40 | 0.803 | 0.520 | 655.0 | 10.6 | 0.95 | 327 | 25 | 95.4 | 67.25 | OK | 53.5 |
| 17 | BSC-A2 60% + FA 40% | SP-A&B (1:2.5) | - | 55 | 40 | 0.765 | 0.540 | 617.5 | 15.4 | 0.65 | 322 |  |  | 63.75 | - | 57.6 |
| 18 | BSC-A2 60% + FA 40% | SP-A&B (1:2.5) | - | 55 | 40 | 0.765 | 0.540 | 565.0 | 13.1 | 0.77 | 319 |  |  | 60.25 | - | 55.0 |
| 19 | BSC-A2 60% + FA 40% | SP-A&B (1:2.5) | 0.05 | 58 | 40 | 0.830 | 0.550 | 627.5 | 12.8 | 0.78 | 323 | 42 | 92.0 | 65.00 | OK | 48.3 |

hydration has to be taken into account when SCC is applied. To reduce the heat of hydration, replacement of cement by limestone powder or fly ash was examined.

The limestone powder is commonly used to reduce the cement content of SCC in Japan. The same strategy was followed with a German limestone powder, but the flowability was not retained sufficiently when 50% of powder volume was substituted by the limestone powder. Mixture No.11 in Table 3.8 shows the result mentioned. SP-E has no problem with the Japanese limestone powder, generally. However, the compatibility with the German one resulted in unsatisfactory results. It is expected from this result that the limestone powder used has a bad influence on the adsorption of superplasticizer and it causes short retention of the concrete flowability. In the case of mixture No.12, the volume of limestone powder was reduced to 25% of the powder volume, and then the concrete flowability was retained sufficiently. These results imply that the limestone powder used is applicable only in a small replacement to the cement. Therefore, it was concluded that the limestone powder applied was not a suitable material for this investigation. However, this conclusion does not mean that all limestone powders in the European market are not applicable to SCC.

Among the mixture No.13-19, fly ash was applied and it didn't show any negative influence on the flowability retention when using up to 40% of the powder volume. The fly ash showed a very satisfactory behaviour.

### 3.5.5 Applicability of welan gum

The ability of welan gum to stabilize the behaviour of fresh concrete has been already verified (see 2.4.3) [13] [60]. In this investigation, welan gum was applied to the same mix design system with the powder type SCC and the designed concretes performed satisfactorily. It showed no negative influence on the behaviour of SCC.

Viscosity modifying admixtures, e.g. welan gum, would not be necessary to produce SCC if the material conditions were always well controlled. However, the material characteristics fluctuate frequently throughout the continuous concrete production and it may cause property variation even more than in the expected range. Welan gum is known as a material which reduces the sensitivity of SCC properties against the material characteristics fluctuation and the variation of temperature as well, and makes the quality control practically sure.

### 3.5.6 Choice of superplasticizer

Among the superplasticizers A-D, only B showed acceptable performance of the flowability retention. However, it has a weak initial dispersibility and requires more time to be active than the other ones. The mixtures No.2, 6-8 and 12-15 in Table 3.8 were mixed with SP-B. They showed a small initial slump flow but the target values were reached after 10-15 minutes (values in brackets). This characteristic is not practical. Therefore, a combination of SP-A and B is considered to be more suitable because SP-A has a strong initial dispersibility and can supplement the weak aspect of SP-B. The mixtures No.16 and 19 were mixed with the combination of SP-A and B. The mixtures resulted in sufficient initial slump flow and a stable flowability retention during more than 1 hour.

### 3.5.7 Influence of mixing on the adequate value of $V_w/V_p$

In this series of tests, 1.05 times the $V_w/V_p$ value obtained by the mortar test was applied as explained in 3.4.4, because this treatment seemed to be suitable to the mixer used and the mixing procedure applied. Among the mixture No.16-18, this phenomenon was verified. The mixture No.16 was mixed with 5% increased $V_w/V_p$ as well as most other mixtures. It showed very good performance for every test. The mixture No.17 was mixed with the original value of $V_w/V_p$ obtained by the mortar test and the ratio Sp/P was adjusted to make the slump flow controlled. In the case of No.17, the concrete became more viscous than No.16 and resulted in low funnel speed. Then, the filling performance of No.17 was worse than No.16.

Mixture No.18 had completely the same composition as No.17 but the mixing procedure was different, 1 minute more in procedure (c) and half a minute more in procedure (d), as explained in 3.4.4. Then, the concrete resulted in a smaller slump flow and a bigger funnel speed than No.17. This result means that longer mixing makes concrete less viscous. Therefore, the $V_w/V_p$ obtained by the mortar test can be considered to require a long mixing time with this type of mixer, and a 5% increased value is reasonable for the applied mixing procedure.

## 3.6 RECOMMENDATION FOR A SCC NL-PROTOTYPE

As a conclusion of this series of test, a SCC NL-prototype is recommended, with the following composition:

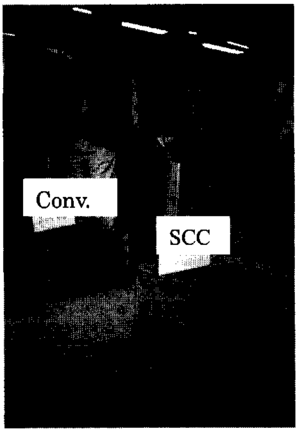
Powder composition : BSC-A 60%+FA 40% in volume
Superplasticizer : SP-A&B combining ratio 1:2.5
Fine aggregate : normal river sand, $S_c/M$=40%
Coarse aggregate : normal river gravel, maximum size=16mm, $G/G_{lim}$=55-58%
Welan gum : 0.05% to water weight (not essential)
Quality control : Slump flow=650±50mm, V funnel=10±2 -13±2 sec. according to $G/G_{lim}$

As mentioned in 3.4.1, the early development of the prototype of Dutch SCC was requested by the Dutch ready-mixed concrete industry. Therefore, it was not aimed in this study to develop a new mixture design method and new testing methods. It was aimed at finding a materials combination and a mixture composition to realize self-compactability of fresh concrete in a limited time and with a limited variation of materials. Therefore, the recommended prototype may not absolutely be the best mixture and material choice in the Netherlands, but it realizes the self-compactability surely and safely.

## 3.7 ACTIVITIES TOWARDS PRACTICAL APPLICATION IN THE NETHERLANDS

### 3.7.1 Open experiment

Through the above process, the Dutch prototype of mix composition for of SCC was determined in September of 1997, and an open experiment was conducted in October of the same year with around 30 related guests in the industry being invited. Table 3.9 shows the demonstrated mixture of the NL-prototype, which corresponds to mixture No.19 in Table 3.8, and a conventional wet concrete (slump 23cm) in comparison. Picture 3.7 shows the result of a filling vessel test for each mixture. The high self-compactability of the NL-prototype is convincingly clear in comparison with a conventional concrete.



Picture 3.7 Result of filling vessel test in the open experiment

Table 3.9 Example of NL-prototype and conventional concrete

| | unit quantity (kg/m$^3$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | W | BSC-A | FA | S | G | SP-A | SP-B | SP-C | Welan gum |
| NL-prototype | 165 | 341 | 180 | 642 | 949 | 0.84* | 2.10* | - | 0.082 |
| conventional | 183 | 340 | - | 832 | 936 | - | - | 1.70* | - |

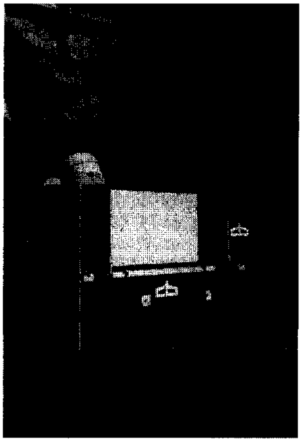
*: volume of SP is included in W

The open experiment surprised the interested parties of the concrete industry in the Netherlands, and convinced them to apply SCC in the future, which significantly prompted the later application studies in this country.

### 3.7.2 Activities on SCC in the ready-mixed concrete industry

**(1) Current application**

After the open experiment, many trials were carried out at ready-mixed concrete companies (see Pictures 3.8-3.10). Since 1998, SCC has been applied in the construction of at least 15 civil structures and buildings, and the total amount of SCC cast reached a value of about 1500 m$^3$ up to October of 1999. Examples are given in the following.



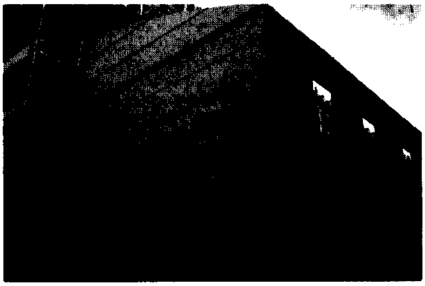
Picture 3.8 Practical investigation in a RMC company (Cementbouw B.V)

Picture 3.9 Practical investigation in a RMC company (Cementbouw B.V)

Picture 3.10 Practical investigation in a RMC company (Cementbouw B.V)

The first large-scale application was the retrofitting of the Royal Theatre in The Hague (1998). As a particular architectural feature, the façade was provided with horizontal ribs, with a triangular cross-section. In the sunlight, the ribs are articulated by their shadows, Picture 3.11.

Since the depth of the ribs was only 8 mm, it was expected that it would not be possible to fill the formwork adequately and to obtain theintended quality of the ribs.



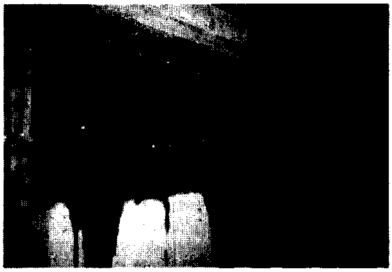
Picture 3.11 Repairing the royal theater (The Hague)

It was the role of SCC to adequately fill the narrow part (rib part) and to give a high surface quality, and therefore a concrete with high flowability (slump flow: 730mm) and somewhat low viscosity (V funnel time: 8 – 9 seconds) as SCC, was chosen. During the construction, the concrete was cast by 4 workers at the beginning, but soon the number of workers was reduced to 2 because the consolidating work was not necessary, so the effect of the use of SCC was also reflected in the rationalization of construction process (see Picture 3.12).

Picture 3.12 Repairing the Royal Theater (The Hague)

In another project SCC was applied in the construction of the side walls and the middle walls of a tunnel under a traffic square in front of the Hague central station (1998-1999). For the construction of the tunnel, the upper slab was constructed before the side and middle walls, in order to restore the traffic facilities as quickly as possible. Because of this, it was impossible to cast concrete into the walls from the upper side in a regular way. In addition, the reinforcement was densely arranged, and therefore the construction using conventional concrete would be extremely difficult (see Picture 3.13).

Hence, the side and middle walls were constructed by casting SCC through a hole with a diameter of about 100 mm, which was provided in the upper slab. Figure 3.3 shows the cross section of the tunnel side wall. As regards the dimensions of the of walls, the large one was 25 m long, 5 m high and 0.7 m thick. The distance between the holes for casting was about 5 m.



**Picture 3.13 Reinforcement of wall of the opencut tunnel (The Hague)**

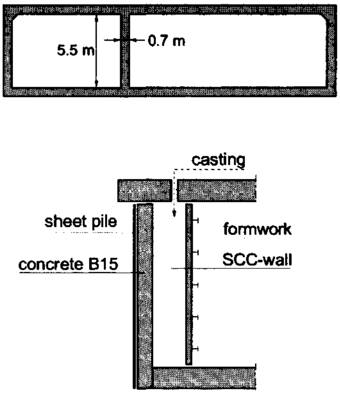


Figure 3.3 Cross section of the tunnel side wall

Table 3.10 Example of SCC mix composition practically applied

| | Slump Flow (mm) | V funnel flow time (sec) | Unit quantity (kg/m$^3$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | W | BSC | FA | S | G | SP-A | SP-B |
| SCC | 680 | 11.8 | 181* | 378 | 200 | 714* | 818* | 0.95 | 1.68 |

*aggregate weight is based on dry condition

water weight includes absorbed water in aggregate

During casting, however, it turned out that 1-2 holes were enough for a tunnel unit to cast SCC, and most of the holes were used for air outlet and confirmation of filling by the overflow of concrete. The mix composition of the concrete used is shown in Table 3.10, and the casting situation is shown in Picture 3.14. The filling ratio of the filling vessel test was 96%, and the cube strength at an age of 28 days was 58 N/mm$^2$. The homogeneity of the concrete appeared to be extremely good after the mould was removed, and the surface quality was very fine.

In the construction, about 30 units of walls were built using SCC, and the casting volume was about 650 m$^3$, which was the largest application in the Netherlands up to October of 1999.

Picture 3.14 Casting SCC for the opencut tunnel (The Hague)

Besides this work, at least 4 applications examples in tunnel construction have been reported after 1998. In addition, SCC was used in the construction of a part of a museum in Leiden and the swimming pool for sea-lions in the Zoo of Rotterdam, in order to have more freedom in the architectural design.

**(2) Standardization of test methods**

In the Dutch ready-mixed concrete industry, standards have been established for the determination of the mix composition for SCC and test methods for quality control. In the followings the standardized test methods are listed:

1) Slump flow test

2) V funnel test

3) Self-compactability test using box-shape apparatus

4) Filling vessel test ( Kajima Vessel Test)

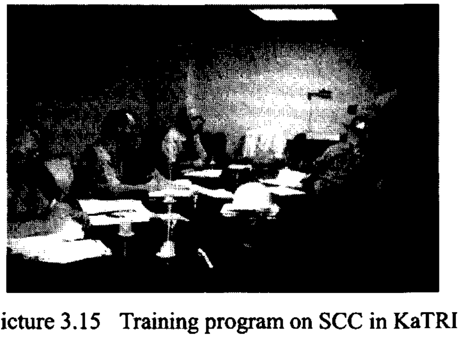
5) Paste flow test for water retaining ratio of powder materials

6) Mortar flow and funnel test for the determination of the adequate water to powder volume ratio.

### 3.7.3 Activities on SCC in the precast concrete industry

**(1) Process of activities**

Almost all the companies manufacturing precast concrete in the Netherlands are members of an association named BFBN. In an organisation named BELTON inside this association, which consists of 24 companies manufacturing structural precast members such as beams, columns, walls and girders for civil structures and buildings, the discussion on the introduction of SCC was initiated around the beginning of 1998. As the most efficient way to develop SCC for their use, the organisation decided to seek cooperation with Japanese experts, and formally asked cooperation with Kajima Technical Research Institute (KaTRI) through the Dutch Ministry of Economy, according to an agreement on science and technology cooperation between Japanese and Dutch governments. In September of 1998, four representatives on behalf of major companies in BELTON visited Japan, and attended a training course prepared by KaTRI (see Picture 3.15). The author was the instructor of this program. The participants learned the theoretical background of mix design of SCC and the 'know-how' on manufacturing and application of SCC.



Picture 3.15 Training program on SCC in KaTRI

After the training the members returned to their country and an intensive SCC development program was started by BELTON to find the mix compositions of SCC that meet its manufacturing conditions. The fundamental research required for the project was conducted at Eindhoven University of Technology.

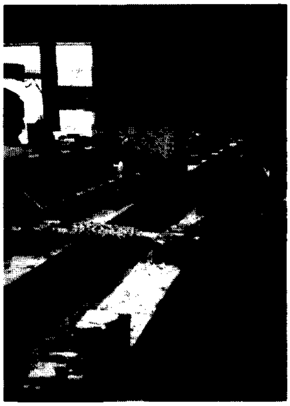
### (2) Required quality (objective of development )

For SCC as used in precast concrete members, the main required quality standards of BELTON are as follows:

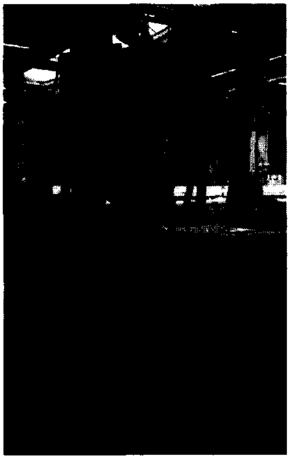
1) The mix composition should assure reproducibility and a stable quality.
2) The mixing method should not be special, and should match the manufacturing cycle.
3) Within one hour after casting the finishing the work should be possible.
4) After the mould has been removed, the surface should be smooth without significant colour unevenness, and with neglectabe air bubble trace.
5) In the case of PC members, the average compressive strength 14±2 hours after casting should be equal or higher than 35N/mm$^2$, and the cube strength at an age of 28 days should be around 55 or 65 N/mm$^2$.
6) In the case of RC members, the average compressive strength 14±2 hours after casting should be equal or larger than 25N/mm$^2$, and the cube strength at an age of 28 days should be around 45 or 55 N/mm$^2$.
7) The increment of material cost should balance by savings on the man hour consumption.

### (3) State of development

In the project of BELTON, whereas the design of the mixtures was basically conducted according to the mix designing system for general-purpose high performance concrete, the basic tests were performed at Eindhoven Technology University, in order to determine the appropriate combination of cement, other powder materials and various types of superplasticizer existing in the Dutch market. Each team representing several companies performed mixing tests and casting tests (see Pictures 3.16 and 3.17), and investigated practical mix compositions respectively. In addition, an investment was carried out for facilities such as silos, mixers and concrete conveying facilities, which were suitable for SCC, and most of member companies became capable of manufacturing products using SCC in December of 1999.



Picture 3.16 Casting test of SCC into beam elements in a precast concrete factory



Picture 3.17 Casting test of SCC into wall elements in a precast concrete factory

In 2000-2001, the BELTON members shared the essential knowledge and experience on SCC. Two training courses in 8 sessions based on the theory and the practise were provided for the representatives of BFBN members. As a result of the dissemination of knowledge, in 2002 more than 60 companies were able to design and apply SCC. The produced SCC volume in 2001 was approximately 150.000 $m^3$. BFBN and BELTON contributed to the national research program on SCC supervised by "Stichting CUR" and executed at Delft University of Technology in Delft. The "CUR - Aanbeveling" (Recommendation concerning the application of SCC) was published in September 2002. The research project on the fire resistance of structural SCC elements, supervised by "Stichting CUR" and performed at the Magnel Laboratories of Gent

University of Technology in Belgium, were completed and reported in the autumn of 2002. R&D projects to modify the manufacturing technology as well as to design and produce new products followed.

The initial costs of the constituent materials for SCC are € 5 to € 10/m$^3$ higher than for the usual fresh concrete. The savings on labour costs during the casting operations compensate these higher materials costs mostly, depending on the type of product. The casting speed increases, and the number of workers involved decreases. However the investments in improving the mixing operations, storage of fillers, concrete transport, temporarily storage and casting units are then not yet taken into account.

The introduction of SCC required not only the modification of the installations but also the training of the workers, because the casting process with SCC and the finishing process of the members after some hours are completely different from the usual practise. On the other hand, another essential aspect is the improvement of the working conditions; a strong reduction of the noise level $\leq$ 85 dB, vibration damages and dust. Many actions during the casting operations can be done by one or two workers with much less effort than with conventional concrete.

## 3.8 CONCLUDING REMARKS

(1) The mix design system of general-purpose SCC is applicable to Dutch materials.

(2) It is necessary to choose an adequate superplasticizer concerning the flowability retention to use SCC practically. The combination of SP-A and B is the best superplasticizer among the tested ones which are available on the Dutch market.

(3) When using 4-16mm coarse aggregate, 55-58% of $G/G_{lim}$ is reasonable to design SCC.

(4) The limestone powder used in this research is not satisfactorily compatible with the applied superplasticizer with regard to the flowability retention. Fly ash resulted in good performance.

(5) Welan gum is applicable to the general purpose approach and showed no negative influence on the SCC quality. The ability of this material to stabilize the SCC quality against material fluctuations is very useful for practical applications.

(6) An adequate water to powder ratio must be found considering the mixing efficiency.

(7) The SCC NL-prototype showed a convincing clear self-compactability in comparison with a conventional wet concrete.

(8) After this development, the practical investigation of SCC was intensified in the Netherlands and SCC is now ready to be used in both the ready-mixed and the precast concrete industries.

# CHAPTER 4
# INFLUENCE OF SILICA FUME, MICRONIZED FLY ASH AND COAL GASIFICATION FLY ASH ON THE FRESH AND HARDENED PROPERTIES OF SCC

## 4.1 INTRODUCTION

In Chapter 3, the NL-prototype SCC mixture was investigated and a suitable composition was recommended. In this recommendation, the strength level of the SCC was not specified as a purpose of the mixture design: this resulted in a 28-day cube compressive strength of about 50 N/mm$^2$. However, different strengths of concrete may be required for practical applications in real structures. Therefore, a "menu" of various strengths of SCC should be prepared in order to make it suitable for practice.

In order to control the strength of SCC, limestone powder is popular in Japan replacing a part of the powder material (cement) but maintaining the necessary amount of the powder to realize self-compactability of the fresh concrete. A larger replacement reduces the strength after hardening, because the limestone powder is chemically passive and does not contribute to the strength development. It is generally possible to control the compressive strength in the range 20-80 N/mm$^2$ by controlling the replacing percentage of the lime stone powder and the cement.

However, it is difficult to produce SCC with a higher strength than 100 N/mm$^2$ using only ordinary cement as a powder material. Of course it is possible to get such a high strength making the water to cement ratio very low, but then it is expected that the mixture loses its self-compactability in the fresh state due to a too high viscosity. Therefore, "something else" should be added to lubricate the mixture in order to realize self-compactability and super-high strength simultaneously.

In Chapter 2, it was shown how self-compacting mixtures get their favourable properties in the fresh state (see 2.2.5). The aggregate particles are surrounded by a thin layer of paste with special properties, which reduces the internal friction in the flowing concrete. A similar mechanism occurs in the paste itself, where the cement (powder) particles are surrounded by a thin water layer (see Figures 2.15 and 2.16). In case of a super-high strength mixture, the amount of the excess water is smaller than in a mixture with adequate self-compactability due to the lower water to cement ratio. Therefore, the cement particles interact with each other and the internal friction in the paste of flowing concrete is high. That causes a too high viscosity, and the required workability and self-compactability cannot be realized. In order to improve this situation, microfillers like silica fume, which consist of particles much smaller than the cement particles, could play a role to reduce the interaction of cement particles and to lubricate the behaviour of the moving paste. Furthermore, such microfillers are expected to contribute to the strength development by a high degree of pozzolanic activity and a geometric packing effect, the so-called “microfiller effect”.

In order to study the effect of such microfillers and develop the optimum mixture composition of super-high strength SCC, tests have been carried out on three types of microfillers with different properties: silica fume (SF), micronized fly ash (MFA) and coal gasification fly ash (CGFA).

## 4.2 MIX DESIGN PHILOSOPHY AND MATERIALS

### 4.2.1 Mix design philosophy

In this study, the general purpose approach recommended by *Okamura* et al. [8] is basically applied as the SCC mixture designing system. The details of the mixture designing system were described in 2.2.3 and 3.2.2.

In order to design the mixture composition of SCC, the estimation of a proper water to powder volume ratio ($V_w/V_p$) is very significant to obtain adequate viscosity, in other words adequate segregation resistance of the fresh concrete. However, the value of the adequate $V_w/V_p$ is strongly dependent on the characteristics of the powder composition applied and the properties of the fine aggregate as well. According to the original method of the general purpose mixture design system, the adequate ratio $V_w/V_p$ should be determined by the mortar test through the procedure of trial-and-error for each powder composition which the designer wants to use. This is a very important step to design a guaranteed good performance of SCC, but it is time consuming. Therefore, *Ouchi* et al. investigated and developed a simplified method for the estimation of the adequate $V_w/V_p$ by as few as possible mortar tests [16]. This method was explained in 2.2.4 and will be used here to determine the adequate ratio $V_w/V_p$ for the materials applied in this investigation.

### 4.2.2 Materials

#### (1) General

As mentioned before, the purpose of this investigation is to find the appropriate material combination to realize super-high strength self-compacting concrete which has a high-level self compactability at the fresh state and a cube compressive strength higher than 100 N/mm$^2$ at 28 days simultaneously. For this purpose, the following materials were chosen from the Dutch market and their availability was examined.

#### (2) Cements and fly ash

Table 4.1 shows the characteristics of the applied cement and fly ash. The BSC is a Dutch common blast furnace slag cement, CEMIJ CEM III/B 42,5 LH HS. The PC is a Dutch Portland Cement, ENCI CEM I 52,5 R. The FA is a Dutch common Fly ash, Amer 9. The particle size distribution curves are presented in Figure 4.1.

Table 4.1 Characteristics of the cements and fly ash

| Material name | Brand | Density (g/cm$^3$) | Blaine (m$^2$/kg) | Clinker (%) | Slag (%) | Fly ash (%) | CaO (%) | $SiO_2$ (%) |
|---|---|---|---|---|---|---|---|---|
| Blast furnace slag cement (BSC) | CEMIJ CEM III/B 42,5 LH HS | 2.94 | 398 | 20.5 | 74.1 | 1.2 | 43 | 28 |
| Portland Cement (PC) | ENCI CEM I 52,5 R | 3.16 | 514 | 100 | - | - | 64 | 20 |
| Fly ash (FA) | Amer 9 | 2.26 | 338 | - | - | 100 | 6.4 | 54 |

#### (3) Microfillers

In this study, the application of microfillers which have a much smaller particle size than the cements applied are considered to obtain sufficient compressive strength of the hardened concrete without losing the workablity and the self compactability of the fresh concrete. In order to investigate the efficiency, silica fume (SF), micronized fly ash (MFA) and coal gasification fly ash (CGFA) were applied. Table 4.2 shows the characteristics of the microfillers investigated. Figure 4.1 shows the particle size distribution curves. SF is a normal product on the Dutch market. MFA is a processed fly ash to obtain the fine particles by a special milling process. CGFA is a fine fly ash which is produced through the process of thermal power generation using gasified coal. The particles of MFA and CGFA are shown in Pictures 4.1 and 4.2 respectively. For the actual use of these materials in this experimental study, they are supplied as slurries of 50% weight concentration.

Table 4.2 Characteristics of the microfillers

| Material name | Brand | Dry substance | | | | | Slurry concentration (%) |
|---|---|---|---|---|---|---|---|
| | | Density (g/cm$^3$) | Blaine (m$^2$/kg) | BET (m$^2$/g) | Ave. Dia. (μm) | SiO$_2$ (%) | |
| Silica fume (SF) | GUGLA | 2.20 | - | 20.0 | 0.15 | 94 | 50 |
| Micronized Fly ash (MFA) | KEMA | 2.62 | 1644 | 10.6 | - | 47 | 50 |
| Coal Gasification Fly ash (CGFA) | Vliegas-unie | 2.45 | 1459 | 5.7 | - | 67 | 50 |

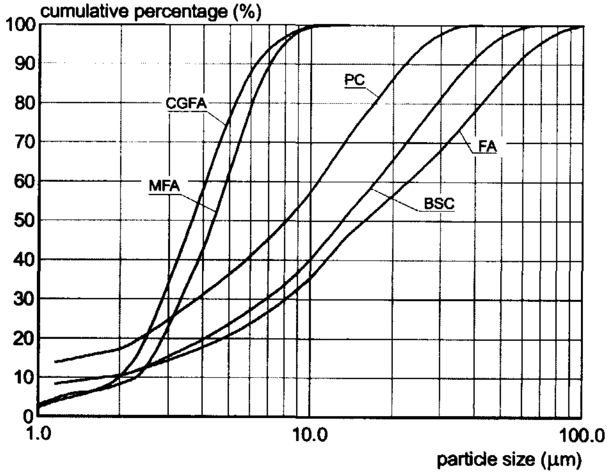
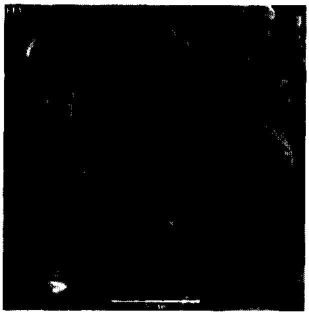
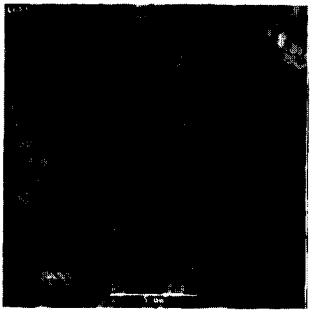


Figure 4.1 Particle size distribution curves of powders



Picture 4.1 Micronized fly ash (MFA)



Picture 4.2 Coal gasification fly ash (CGFA)

### (4) Chemical admixtures

Table 4.3 shows the characteristics of the applied superplasticizers. SP-A and B are the superplasticizers of the type polycarboxylic ether complex. Both of them are products from the Dutch market. SP-B has a similar active polymer as SP-A but the initial dispersibility is lower than A. However, SP-B has a better ability of slump retention. In order to obtain a sufficient stability of the mixture during the test, SP-A and B are used together. The combining ratios between both superplasticizers are dependent on the powder composition applied.

Table 4.3 Characteristics of the superplasticizers

| | Product name | Chemical description | Density* ($g/cm^3$) | Solid concentration (%) |
|---|---|---|---|---|
| SP-A | Glenium 51 | Polycarboxylic ether complex | 1.10 | 35 |
| SP-B | Glenium 27 | Polycarboxylic ether complex | 1.05 | 20 |

*solution base

### (5) Aggregate

Table 6.4 shows the characteristics of the fine and the coarse aggregate used. These are typical Dutch river sand and crushed river gravel aggregates. The maximum size of the gravel is 16 mm. The border size between fine and coarse aggregate, the maximum size of the sand, is 4 mm according to the Dutch standard.

In the general purpose approach [8], particles finer than 0.09 mm in the fine aggregate are not considered any more as aggregates but as powders. In this investigation, 0.125 mm is considered as the transition point between the aggregate and the powder because of the different sieve size of the Dutch standard.

Table 4.4 Characteristics of the aggregates

| | Type | Density* ($g/cm^3$) | Absorption (%) | F.M | $\kappa_{sf}$ (%) (<0.125 mm) | Solid volume (%) |
|---|---|---|---|---|---|---|
| Fine aggregate | River sand (0-4 mm) | 2.59 | 0.86 | 2.91 | 1.0 | 68 |
| Coarse aggregate | Crushed River gravel (4-16 mm) | 2.63 | 1.15 | 6.72 | - | 60 |

** saturated surface dry base*

## 4.3 EXPERIMENTAL PART 1: TESTS ON PASTE

### 4.3.1 Objective

In order to develop a super-high strength SCC, the following three powder compositions were chosen as a basis.

(1) BSC 100%
(2) BSC 50% + PC 50%
(3) BSC 60% + FA 40%

The combining ratios mentioned above are based on the solid volume fractions. In this investigation, these three basic powder compositions were partially replaced by SF, MFA or CGFA with the solid volume fractions of 0, 5, 10 or 15 %, respectively. 32 powder compositions in total were applied for the tests including PC, FA alone as well. For each of them, the paste test was executed to determine the overall physical properties of the compositions.

### 4.3.2 Experimental program

In order to determine the properties of the powder compositions applied, the paste flow test was executed. The procedure of the paste test was described in 3.4.2. For each powder composition, the water retaining ratio "$\beta_p$" and the deformation factor "$E_p$" were estimated by plain paste without using any chemical admixture.

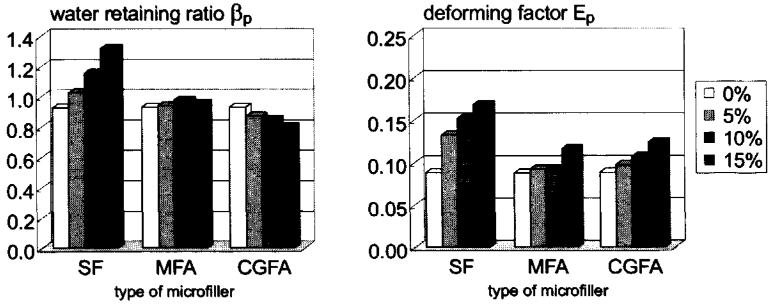
### 4.3.3 Results and discussions

Figures 4.2(a)-(c) show the influence of microfillers on the $\beta_p$ and $E_p$ estimated by the paste test. In case of the basic compositions (1) BSC 100% and (2) BSC 50% + PC 50%, the overall powder mixtures were partially replaced by the microfillers with the volume fractions of 5, 10 and 15 %. In the case of the basic compositions (3) BSC 60% + FA 40%, the volume fraction of BSC was constant and FA was partially replaced by the microfillers in order to evaluate the difference of efficiency between the normal fly ash and the microfillers.

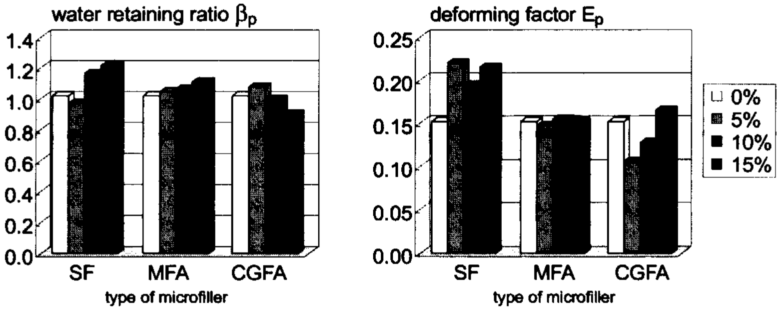
During this experiment, one undesirable phenomenon occurred. When using PC, the pastes mixed were mostly not smooth mixtures and some agglomerated masses were observed. This is because the fineness of PC applied was larger than that of the BSC and FA applied, and because the mixing procedure used was not suitable for this material. However, the mixing procedure was not changed in this series of tests and the fineness was not changed as well. In fact a Blain value of 500 $m^2/kg$ is not excessively fine. Therefore, the test results when using PC indicate some instability, but the results were kept available to evaluate the relative tendency of the influence of microfillers.

The $\beta_p$ determined is the water retaining ratio of each powder composition, which means the water to powder volume ratio for which the deformation of the paste is zero and the void among the powder particles is saturated with water. In other words, a powder which has a larger value of $\beta_p$ requires a larger amount of water to give a particular deformation in the paste flow test. The $E_p$ estimated is the deformation factor of each powder composition. A large value of $E_p$ represents a property of the powder composition which is less sensitively influenced by a deviation of the water powder ratio on the result of the paste flow test.

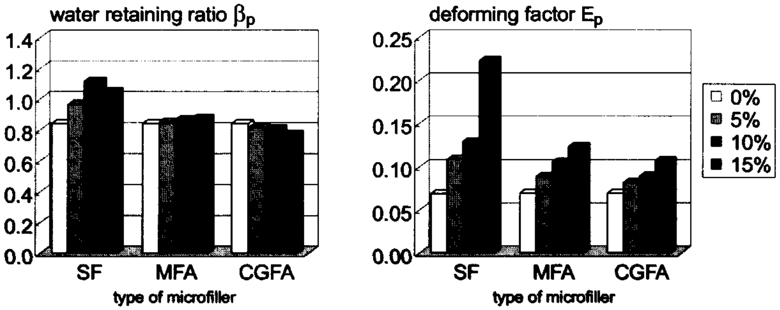
The microfillers, SF, MFA and CGFA, indicate different tendencies concerning the variation of $\beta_p$ due to the replacement of their basic compositions. In the case of the silica fume (SF), the increase of the replacing volume causes a rise of $\beta_p$. This result can be interpreted as follows. The particles of the silica fume retain a large amount of water on their surface both physically and chemically because of their very large surface area and high initial reactivity compared to normal cements. Therefore, the deformability of the paste is spoiled due to the replacement of the basic powder by the silica fume, and a larger replacement results in a larger value of $V_w/V_p$ to give a particular flow diameter.



(a) basic powder: BSC 100%



(b) basic powder: BSC 50% +PC 50%



(c) basic powder: BSC 60% + FA 40%

Figure 4.2 Influence of microfillers on $\beta_p$ and $E_p$

In the case of the micronized fly ash (MFA), the increase of the replacing percentage is accompanied by a rise of $\beta_p$ as well as for silica fume. However, the degree of this tendency is very small. The MFA is a very fine fly ash which is micronized through a milling process of normal fly ash. Therefore, its particle shape is rough and the roundness of the original particles is lost as shown in Picture 4.1. This implies that a larger amount of water is physically retained on their surface than on the normal size fly ash and even on the cements. However, the fineness and the reactivity are much lower than in the case of the silica fume; especially the initial reactivity of fly ash is known to be lower than that of ordinary cement. Therefore, it is understandable that the degree of the tendency mentioned above is not large for MFA.

Furthermore, the coal gasification fly ash (CGFA) shows a contrary tendency concerning the variation of $\beta_p$. In this case, the increase of the replacing percentage is accompanied by a decrease of $\beta_p$. It means that a paste including a larger amount of CGFA requires a smaller amount of water to give a particular deformability in the flow test executed, or a paste including a larger amount of CGFA gives a larger deformation when the water to powder ratio is constant. This phenomenon can be explained as follows. CGFA is a very fine fly ash which is produced by a process of thermal power generation using the gasified coal. Its roundness is very good as shown in Picture 4.2. This good roundness of the particles possibly leads to a lower amount of water retained on their surface than for normal cements and even for the normal fly ash in spite of their large surface area. However, the roundness of the particles alone seems to be not enough to explain the result. It is likely that the chemical reactivity of CGFA is lower than that of normal fly ash. Anyway, it is clarified by this result that CGFA has a high possibility to enhance the deformability of fresh concrete.

## 4.4 EXPERIMENTAL PART 2: TESTS ON MORTAR

### 4.4.1 Objective

In order to find the proper mixture composition of the mortar in SCC using the powder compositions considered in the previous section, mixing tests on mortar were executed. The basic powder compositions were:

(1) BSC 100%
(2) BSC 50% + PC 50%
(3) BSC 60% + FA 40%

so the same as in the paste tests. Each basic composition was partially replaced by one of the types of microfiller at 5, 10 and 15 % solid volume fractions. Altogether 30 powder compositions were tested and an adequate water to powder volume ratio for each composition was estimated according to Ouchi's evaluation method described in 2.2.4. Moreover, some prismatic specimens were cast for each target mixture and the compressive strength was examined.

### 4.4.2 Experimental program

To estimate the adequate value of $V_w/V_p$ according to the general purpose approach, mortar tests were carried out. The target value was judged on the basis of the evaluation method developed by *Ouchi* et al. which was described in 2.2.4. In this series of tests, the superplasticizers shown in Table 4.3 were used to impart a proper deformability of the mortars. SP-A and B are superplasticizers of the type polycarboxylic ether complex. In order to obtain a sufficient stability of the mixture during the test, SP-A and B are used in combination. However, the proper ratios between both superplasticizers were dependent on the base powder composition applied. Therefore, some preliminary mortar mixtures were conducted to confirm the time dependent stability of the mortar, and the following combining ratios (in weight) were found to be adequate for the three basic powder compositions respectively.

(1) BSC 100% ⇒ SP-A : SP-B = 1 : 1
(2) BSC 50% + PC 50% ⇒ SP-A : SP-B = 2 : 3
(3) BSC 60% + FA 40% ⇒ SP-A : SP-B = 2 : 5

The fine aggregate content in the mortar was kept constant at 40% of the mortar volume. Moreover, particles finer than 0.125 mm in the fine aggregate were not considered as aggregates, but as powders. The testing procedure conducted is explained in the following.

(a) 2-liter of mortar was mixed by a Hobart mixer (model A-200). The mixing time was totally four minutes according to the following procedure. During the first minute, all powder, fine aggregate and the first charge of water ($W_1$) were mixed at a low rotation speed (speed 1). Then, the mortar stuck on the wall of the mixer pot was scratched. During the second minute, the mortar was mixed at a low rotation speed (speed 1). During the third minute, the mortar was mixed with the second part of the water ($W_2$) and a particular amount of superplasticizer at a low rotation speed (speed 1). Then, the mortar stuck on the wall of the mixer pot was scratched again. During the following half a minute, the mortar was mixed at a low rotation speed (speed 1) and then, one minute rest was taken. After the rest, the mortar was mixed at the low rotation speed (speed1) for another half a minute, and the mixing was completed. The first water to powder volume ratio, $V_{w1}/V_p$ is generally taken as 0.7 times $\beta_p$ of the powder composition used. However, when the value of $V_w/V_p$ applied is relatively small compared to the $\beta_p$, the amount of the second charge water becomes very little or a negative value. In such a case, the $V_{w1}/V_p$ is adjusted so that the second water charge becomes at least 50ml.

(b) After the mixing, a mortar flow test was conducted without any shaking of the table and the flow diameters were measured as shown in Figure 2.30. The flow test was executed two times in sequence and the relative flow area of the mortar, $\Gamma_m$, was calculated using the average value of the testing data. After the flow test, the mortar funnel test was executed as soon as possible as shown in Figure 2.31. The funnel test was executed two times in sequence and the relative funnel speed of the mortar, $R_m$, was calculated using the average value of the flow time.

(c) Using a combination of ( $\Gamma_m$ , $R_m$) obtained by testing as explained before and an input value of the $V_w/V_p$, a target value of the adequate $V_w/V_p$ is predicted by the equation (2.3) shown in 2.2.4. However, when the difference between the input value and the calculated value of $V_w/V_p$ is relatively large, the accuracy of the prediction is a bit questionable, because the evaluating method is built up based on experimental data from Japanese materials. Therefore, the testing procedure described above had to be repeated several times until the estimated value converged closely enough to the input value.

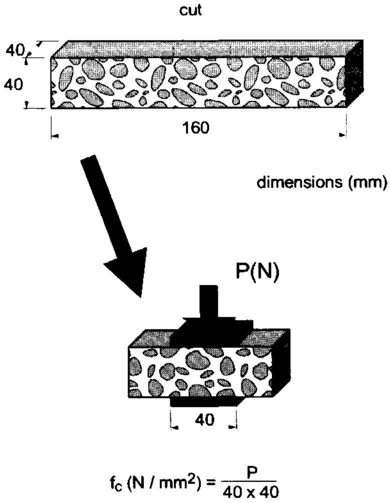


Figure 4.3 Compressive strength test of mortar specimens

(d) When the target value of $V_w/V_p$ for a powder composition had been obtained, six prismatic specimens with dimensions 40×40×160 mm were made of the mortar. The specimens were demoulded 24 hours after casting and cured under water at 20°C. The six specimens were cut into halves after 7 days, i.e. 12 specimens with the dimensions 40×40×80 mm were prepared for a mixture. Three of them were examined to determine the compressive strength at 7, 28, 56 and 91 days in the way shown in Figure 4.3. The average value of three specimens was considered as the compressive strength of the mixture at the age tested. Each specimen was cured under water at 20°C until the testing age.

### 4.4.3 Results and discussions

**(1) Influence of microfillers on the adequate ratio $V_w/V_p$**

The results of the mortar flow and the mortar funnel test are given in Table 4.5. The results of $\Gamma_m$ and $R_m$ represent the fresh properties of the mortars with the applied $V_w/V_p$ and Sp/P. The target values $V_w/V_p$ were estimated by the equation (2.3) shown in 2.2.4 adopting these results. In some cases, there are small differences between the target values and the applied values of $V_w/V_p$, but more or less they are equivalent.

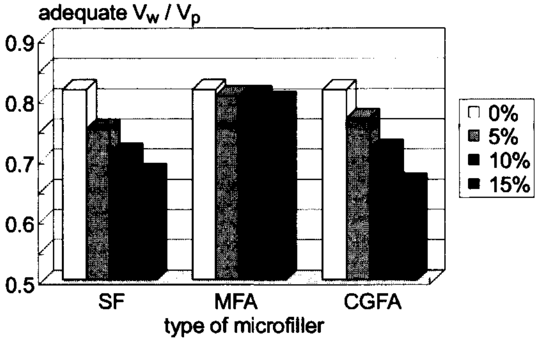
Figures 4.4(a)-(c) show the influence of partially replacing the basic powder compositions by microfillers for the value of the adequate ratio $V_w/V_p$ determined according to the general purpose approach. In the case of the silica fume (SF), the values of the adequate $V_w/V_p$ decrease for an increase of the replacing percentage. In the mix proportioning of SCC, a change of $V_w/V_p$ strongly influences the viscosity of a mixture, i.e. a larger $V_w/V_p$ normally results in a lower viscosity when the same material composition is applied. In this experiment, $V_w/V_p$ was controlled to obtain mixtures which have a constant viscosity represented by a constant result of the mortar funnel test. Therefore, the results shown in Figures 4.4(a)-(c) mean that the use of silica fume decreases the viscosity of the mortar, and a powder composition including a larger amount of the silica fume requires a lower value of $V_w/V_p$ to obtain a constant viscosity of mixtures.

On the other hand, the use of the micronized fly ash (MFA) does not decrease the value of the adequate $V_w/V_p$ significantly compared to SF. When it is used to replace BSC or BSC+PC (see Figures 4.4(a) or (b)), the value of the adequate $V_w/V_p$ barely decreases with the increase of replacement. However, when it is used to replace the normal fly ash (see Figure 4.4(c)), the value of adequate $V_w/V_p$ increases a little. This seems to be because of the smaller roundness of the MFA particles, and it can be concluded that the MFA does not work to decrease the viscosity of the mixtures.

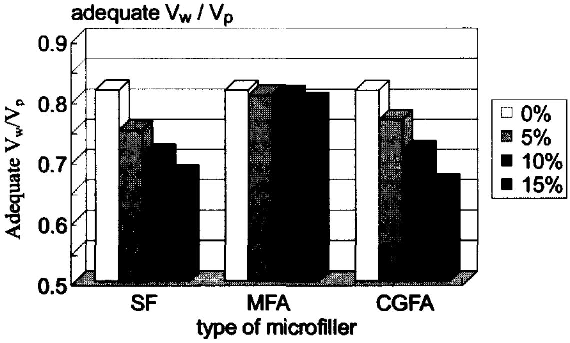
The coal gasification fly ash (CGFA) applied in this study showed a tendency very similar to the effect of silica fume concerning the reduction of the adequate ratio $V_w/V_p$, i.e. the reduction of the viscosity in spite of its lower fineness than the silica fume. The Blaine value of CGFA is nearly the same as that for the MFA, but the roundness of the particles of the CGFA is much better than the MFA as shown in Picture 4.1 and 4.2. Therefore, it can be evaluated that CGFA can make the mortar mixtures smoother, in other words less viscous, than MFA when replacing the basic powder compositions tested.

Table 4.5 Results of mortar flow and funnel test

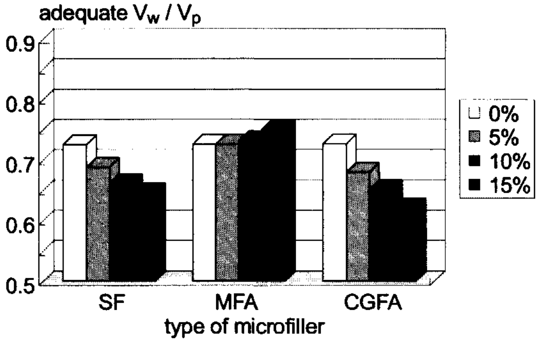
| Powder Composition | Mixture name | **Target $V_w/V_p$** | Applied $V_w/V_p$ | Applied Sp/P | $\Gamma_m$ | $R_m$ |
|---|---|---|---|---|---|---|
| BSC 100% | BS100 | **0.815** | 0.815 | 0.55 | 5.20 | 1.04 |
| BSC 50% + PC 50% | BSPC100 | **0.835** | 0.835 | 0.91 | 4.07 | 0.94 |
| BSC 60% + FA 40% | BSFA100 | **0.725** | 0.725 | 0.70 | 5.84 | 1.07 |
| BSC 95% + SF 5% | BSSF5 | **0.750** | 0.750 | 0.67 | 3.85 | 0.90 |
| BSC 90% + SF 10% | BSSF10 | **0.710** | 0.705 | 0.86 | 3.26 | 0.82 |
| BSC 85% + SF 15% | BSSF15 | **0.675** | 0.670 | 1.20 | 3.87 | 0.87 |
| BSC 95% + MFA 5% | BSMF5 | **0.805** | 0.810 | 0.58 | 4.51 | 1.00 |
| BSC 90% + MFA 10% | BSMF10 | **0.805** | 0.805 | 0.62 | 4.39 | 0.96 |
| BSC 85% + MFA 15% | BSMF15 | **0.795** | 0.795 | 0.71 | 4.85 | 1.00 |
| BSC 95% + CGFA 5% | BSCF5 | **0.765** | 0.770 | 0.55 | 5.20 | 1.06 |
| BSC 90% + CGFA 10% | BSCF10 | **0.715** | 0.720 | 0.59 | 5.26 | 1.06 |
| BSC 85% + CGFA 15% | BSCF15 | **0.660** | 0.660 | 0.58 | 4.94 | 1.00 |
| BSC 47.5% + PC 47.5% + SF 5% | BSPCSF5 | **0.775** | 0.775 | 1.40 | 4.22 | 0.94 |
| BSC 45% + PC 45% + SF 10% | BSPCSF10 | **0.755** | 0.750 | 1.80 | 3.94 | 0.87 |
| BSC 42.5% + PC 42.5% + SF 15% | BSPCSF15 | **0.715** | 0.710 | 2.60 | 4.23 | 0.88 |
| BSC 47.5% + PC 47.5% + MFA 5% | BSPCMF5 | **0.830** | 0.830 | 1.00 | 4.72 | 0.97 |
| BSC 45% + PC 45% + MFA 10% | BSPCMF10 | **0.825** | 0.825 | 1.10 | 4.94 | 1.01 |
| BSC 42.5% + PC 42.5% + MFA 15% | BSPCMF15 | **0.820** | 0.820 | 1.15 | 4.70 | 0.96 |
| BSC 47.5% + PC 47.5% + CGFA 5% | BSPCCF5 | **0.790** | 0.790 | 0.99 | 4.10 | 0.90 |
| BSC 45% + PC 45% + CGFA 10% | BSPCCF10 | **0.765** | 0.760 | 1.07 | 4.94 | 0.95 |
| BSC 42.5% + PC 42.5% + CGFA 15% | BSPCCF15 | **0.720** | 0.725 | 1.09 | 5.10 | 1.04 |
| BSC 60% + FA 35% + SF 5% | BSFASF5 | **0.695** | 0.695 | 0.90 | 4.30 | 0.95 |
| BSC 60% + FA 30% + SF 10% | BSFASF10 | **0.660** | 0.655 | 1.20 | 4.12 | 0.89 |
| BSC 60% + FA 25% + SF 15% | BSFASF15 | **0.645** | 0.640 | 1.60 | 4.14 | 0.87 |
| BSC 60% + FA 35% + MFA 5% | BSFAMF5 | **0.725** | 0.720 | 0.70 | 5.16 | 0.98 |
| BSC 60% + FA 30% + MFA 10% | BSFAMF10 | **0.730** | 0.725 | 0.79 | 5.11 | 0.97 |
| BSC 60% + FA 25% + MFA 15% | BSFAMF15 | **0.750** | 0.750 | 0.77 | 3.61 | 0.88 |
| BSC 60% + FA 35% + CGFA 5% | BSFACF5 | **0.680** | 0.680 | 0.67 | 5.09 | 1.01 |
| BSC 60% + FA 30% + CGFA 10% | BSFACF10 | **0.650** | 0.650 | 0.68 | 5.21 | 1.02 |
| BSC 60% + FA 25% + CGFA 15% | BSFACF15 | **0.620** | 0.620 | 0.67 | 4.72 | 0.99 |



(a) basic powder: BSC 100%



(b) basic powder: BSC 50% + PC 50%



(c) basic powder: BSC 60% + FA 40%

Figure 4.4 Influence of microfillers on adequate $V_w/V_p$ in mortar

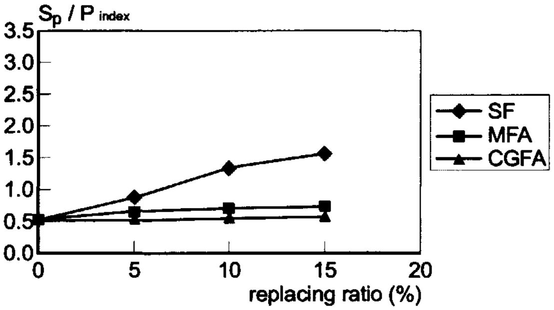
**(2) Influence of microfillers on the dosage of superplasticizer**

From the test results shown in Table 4.5, it is possible to evaluate the influence of microfillers on the dosage of superplasticizer necessary to obtain a particular flowability when applying the adequate $V_w/V_p$ for each powder composition. In this series of experiments, it was tried to control the relative flow area of mortar, $\Gamma_m$, at a constant value of 5.0. However, the values obtained more or less deviate from the target. Therefore, the influence of microfillers on the proper dosage of superplasticizer cannot be evaluated directly with the values of the applied Sp/P. In order to estimate it correctly, but relatively, the following index is employed here.

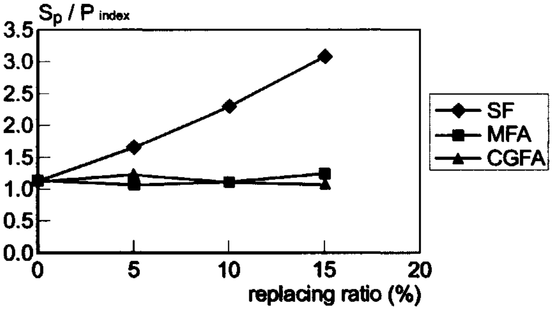
$$Sp / P_{INDEX} = (Sp / P_{APPLIED}) \cdot \left( \frac{5.0}{\Gamma_m} \right) \qquad (3.1)$$

In Figures 4.5(a)-(c), the variations of $Sp/P_{INDEX}$ due to the replacing percentage of microfillers are graphically presented. In these figures, it is very clear that the increase of the replacing percentage of the SF linearly raised the $Sp/P_{INDEX}$. For all basic powder compositions applied, 15% replacement by SF resulted in an approximately three times larger value of the $Sp/P_{INDEX}$ than the value for the basic mixture (0% microfiller). In other words, when using a larger amount of the SF in a mortar mixture, a larger amount of superplasticizer is required to realize a particular flowability. In this case, it should be of course considered that the substantial reduction of $V_w/V_p$ as shown in Figures 4.4(a)-(c) has its effect on the increase of *Sp/P*, but it does not seem to be sufficient to explain the large variation.

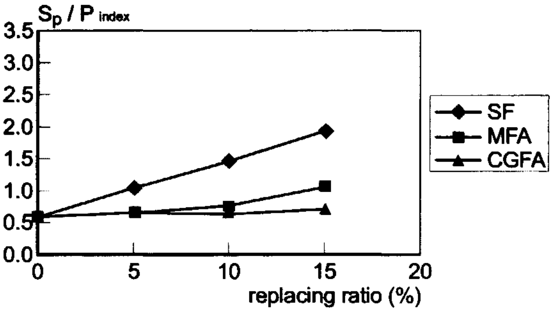
Furthermore, MFA and CGFA show tendencies different from SF concerning the dosage of superplasticizer. According to the result shown in Figures 4.5(a)-(c), the use of MFA replacing the basic powder compositions generally slightly increases the $Sp/P_{INDEX}$. In this case, the small increase of $Sp/P_{INDEX}$ seems to supplement the small reduction of $V_w/V_p$ (see Figures 4.4(a)-(c)) to obtain a particular flowability. However, almost no increase of $Sp/P_{INDEX}$ is recognized due to the use of CGFA in spite of the substantial reduction of $V_w/V_p$. This tendency is very different from the case of SF and MFA mentioned before and verifies that the variation of *Sp/P* cannot be explained only by the variation of $V_w/V_p$. In the following section, this phenomenon is further discussed.



(a) basic powder: BSC 100%



(b) basic powder: BSC 50%+PC 50%



(c) basic powder: BSC 60%+FA 40%

Figure 4.5 Influence of microfillers on dosage of superplasticizer in mortar

**(3) Discussing the influence of microfillers on the properties of fresh mortar**

As mentioned in the previous sections, the use of microfillers influences the properties of the fresh mortar, and influences both the values of $V_w/V_p$ and *Sp/P* necessary to realize the same properties in the flow test and the funnel test. However, the tendencies of the variation are different for each microfiller, SF, MFA and CGFA. In order to understand the difference, individual characteristics of the various microfiller particles are considered. Table 4.6 shows the summary of the tendencies on how the microfillers influence the behaviour of the fresh paste and the mortar, and the supposed characteristics of the individual particles.

Table 4.6 Influence and particles' characteristics of microfillers (summary)

| | | SF | MFA | CGFA |
|---|---|---|---|---|
| Influence on test result | $\beta_p$ | ⇑ | ↑ | ↓ |
| | adequate $V_w/V_p$ | ⇓ | ↓ | ⇓ |
| | *Sp/P* | ⇑ | ↑ | ≈ |
| Particles' characteristics | Fineness | very high | high | high |
| | Roundness | good | not good | good |
| | Initial reactivity | high | low | Low |
| | SP adsorptivity | high | low | Low |

⇑ : large increase ↑ : small increase
⇓ : large decrease ↓ : small decrease
≈ : little variation

As explained in section (1), SF and CGSF showed a very similar effect on the reduction of the adequate $V_w/V_p$. When looking into the characteristics of individual particles, SF and CGFA have the same feature only with regard to the fineness, which is higher than for normal binders, and the roundness, which is much better than for normal binders. From this point of view, it can be hypothesized that the deforming resistance, i.e. the viscosity, of mortar mixtures is reduced due to the "lubricant effect" of microfiller particles which have a much larger fineness and a good roundness adsorbing the superplasticizer polymers when a constant $V_w/V_p$ is applied. Therefore, the use of SF and CGFA substantially reduces the $V_w/V_p$ to realize a constant viscosity. MFA also showed a small reduction of the $V_w/V_p$ when it was used to partially replace the basic powder composition BSC 100% and BSC 50% + PC 50% due to its "lubricant effect" provided by the high fineness, as shown in Figures 4.4(a) and (b). However, the reduction is much smaller than for SF and CGFA because of its bad particle roundness. As the evidence of it, the use of MFA replacing normal fly ash in the basic powder composition BSC

60% + FA 40% did not reduce, even increased the adequate $V_w/V_p$ (see Figure 4.4(c)), because the roundness of MFA is much smaller than that of the normal FA.

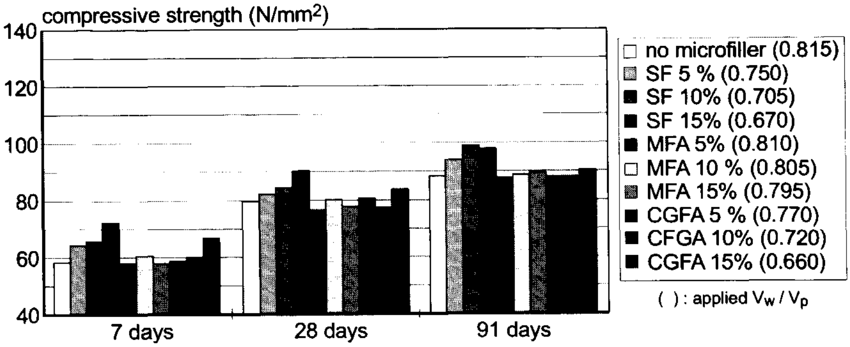
Furthermore, the necessary dosage of superplasticizer is differently affected by the SF, MFA and CGFA. When SF is used, the necessary ratio *Sp/P* is significantly increased. This phenomenon is expected to be caused by a number of reasons which relate to elementary behaviour. Firstly, the use of SF substantially increases the $\beta_p$ of a powder composition in the plain paste flow test. This represents the fact that a powder composition including SF is potentially less deformable than a composition without SF when $V_w/V_p$ is constant. Secondly, the use of SF significantly reduces the ratio $V_w/V_p$ to obtain a particular viscosity, but the reduction of $V_w/V_p$ spoils the deformability of the mixture if *Sp/P* is constant. Thirdly, the adsorptivity of superplasticizer polymers to the surface of SF particles is supposed to be very intense because of its high initial reactivity and high fineness. These three phenomena work together in increasing the dosage of superplasticizer necessary to realize a particular flow diameter in the mortar flow test.

According to the same viewpoint, the influence of MFA and CGFA on the dosage of superplasticizer can be understood, and as a consequence, they do not require so much superplasticizer to obtain the same level of flowability of mortar accompanied by the proper viscosity.

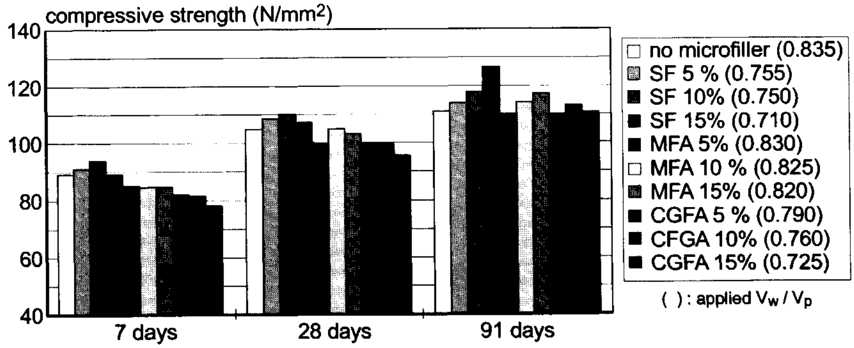
### (4) Influence of microfillers on the strength of an SCC mortar

Figures 4.6(a)-(c) show the results of the compressive strength tests at 7, 28 and 91 days for three different basic powder compositions respectively, for the test specimens 40×40×80 mm as shown in Figure 4.3. For each microfiller, the compressive strengths for 0, 5, 10 and 15 % replacement of basic powder are indicated parallel to each other. Here, it should be noticed that the water to powder volume ratio ($V_w/V_p$) applied for each case is not the same. It corresponds to the applied $V_w/V_p$ shown in Table 4.5 which mostly corresponds with the target value of $V_w/V_p$ for each powder composition determined on the basis of the fresh properties.

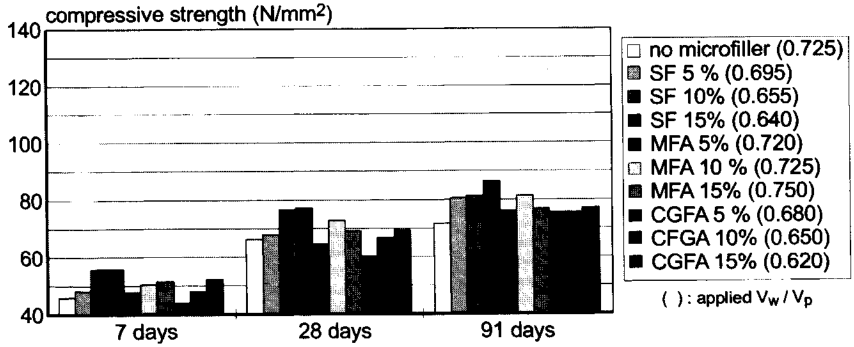
Figure 4.6(a) shows the results for the basic powder composition of BSC 100%. In this case, the compressive strength generally increased as the replacing percentage of SF was raised for any age. On the contrary, the use of MFA and CGFA did not improve the compressive strength and the results were almost constant in spite of the difference in replacing percentage and $V_w/V_p$,



(a) basic powder: BSC 100%



(b) basic powder: BSC 50% + PC 50%



(c) basic powder: BSC 60% + FA 40%

Figure 4.6 Influence of microfillers on compressive strength of mortar especially for CGFA. When CGFA was used to replace BSC, the adequate ratio $V_w/V_p$ was substantially reduced due to the microfiller effect as discussed in the previous section, and it was expected to enhance the compressive strength. However, this was not the case except for 15% replacement. This result implies that the CGFA has a lower pozzolanic activity than SF, even than MFA, and its contribution to the strength development is smaller than that of the basic cement.

Figure 4.6(b) shows the results for the basic powder composition BSC 50% +PC 50%. In this case, the application of SF improved the strength development like in the previous section. At 7 and 28 days, the compressive strength for 15% replacement of cement by SF resulted in a lower value than for 10% replacement, but it was regained after 91 days. As a consequence, 15% replacement of BSC 50% +PC 50% by SF showed the highest compressive strength after 91 days among all the mixtures tested. On the other hand, the use of MFA and CGFA did not improve the strength, even decreased it at relatively young age, e.g. 7 and 28 days. After 91 days, the use of MFA showed a small improvement of the compressive strength, and the use of CGFA resulted in an almost constant strength independently of the replacement volume in spite of the substantial reduction of $V_w/V_p$.

Figure 4.6(c) shows the results for the basic powder composition of BSC 60% + FA 40% replacing a part of FA by the microfillers. In this case, at 91 days, all microfillers showed an improvement of the compressive strength for a larger replacement. SF has the largest effect among them to increase the compressive strength due to its high pozzolanic activity and the $V_w/V_p$ reduction. The results for MFA 15% replacement at 28 and 91 days were lower than for 10% replacement. This is because of the increase of $V_w/V_p$ due to the roughness of the particle shape. CGFA also generally showed an increase of the compressive strength with a larger replacement. However, the magnitude is not very large in spite of the substantial reduction of $V_w/V_p$, and 5% replacement of the basic powder resulted in lower strengths at 7 and 28 days than 0% replacement. This is considered to be caused by the low pozzolanic activity of CGFA, especially at early age.

### 4.4.4 Concluding remarks on the mortar tests

(1) The use of silica fume (SF) and coal gasification fly ash (CGFA) can substantially reduce the viscosity of a mortar mixture when $V_w/V_p$ is constant. As a consequence, the adequate value of $V_w/V_p$ for SCC is reduced by the viscosity reduction effect. The use of micronized

fly ash (MFA) does not contribute to the reduction of the adequate value of $V_w/V_p$ for SCC because of the roughness of the particle shape.

(2) When SF is used to replace the basic powder compositions, the necessary amount of the superplasticizer for obtaining a particular deformability accompanied by an appropriate viscosity increases substantially. MFA and CGFA do not require an additional superplasticizer dosage for a larger replacement percentage.

(3) When SF is used to replace the basic powder compositions, a larger replacement generally results in a higher compressive strength by virtue of its high pozzolanic activity and strong $V_w/V_p$ reducing effect. On the other hand, MFA and CGFA do not improve the strength development very much. In spite of its strong $V_w/V_p$ reducing effect, a larger use of CGFA resulted in a constant or sometimes decreased strength, because of its very low pozzolanic activity.

## 4.5 EXPERIMENTAL PART 3: TESTS ON CONCRETE

### 4.5.1 Objective

In order to confirm the adequacy of the water to powder volume ratio ($V_w/V_p$) for each powder composition estimated in 4.4 for mortar, a number of concrete mixtures were made applying the $V_w/V_p$. The properties of the fresh concretes including the self compactability were examined. Moreover, the compressive strengths of the mixtures were tested. In view of these test results, the influence of the microfillers on the properties in the fresh state and the mechanical properties of the concrete in the hardened state were tried to be understood.

### 4.5.2 Experimental program

Among the 30 powder compositions examined in the mortar tests, 16 combinations were selected to be applied in a concrete test. The selected cases are shown in Table 4.7. The combining ratios SP-A to SP-B are the same as the ones applied in the mortar tests, with a variation according to the basic powder compositions.

In this series, the volumes of coarse and fine aggregate were fixed throughout the whole program, with $G/G_{lim} = 55$ % and $S_c/M = 40$ %. The fine aggregate volume fraction is the same as for the mortar test. The moisture condition of the fine and the coarse aggregate was controlled at wet (the water content was around 2 %) and the amount of mixing water was adjusted with regard to the amount of surface moisture of the aggregates.

In this experiment, a forced pan type of mixer, as explained in 3.4.4 and Picture 3.4, was used to mix the concrete. Figure 4.7 shows the mixing procedure applied to the concrete production. The volume of concrete mixed was 45 liters for each batch. Two batches of concrete were mixed in sequence for a mixture, and they were combined together and tested

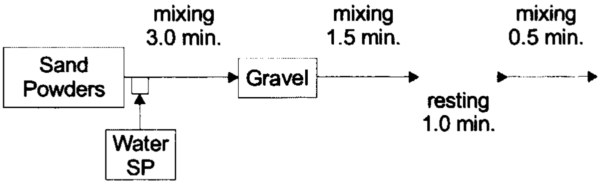


Figure 4.7 Mixing procedure of concrete

For each powder composition, the target value of $V_w/V_p$ as established in the mortar test was applied. After the concrete mixing, the slump flow test and the V funnel test were carried out. The ratio *Sp/P* was adjusted to obtain a proper deformability (slump flow value). In this experiment, a slump flow value=650 ± 50 mm and a V funnel time=13 ± 3 sec were considered as the adequate values for a workable SCC. The box test (see Figure 2.24 and 2.25) and the filling vessel test (see Figure 2.21) were conducted to evaluate the self compactability of the concretes mixed. For these tests, the following values were regarded as sufficient to verify the self compactability of the fresh concrete: (a) The filling height of the box test is larger than 300 mm. (b) The filling ratio in the filling vessel test, F, is higher than 90 %. After all the tests, the slump flow was tested again at approximately 25 minutes after mixing. Furthermore, the examined fresh concrete was placed into cubic moulds whose dimensions were 150×150×150 mm in order to test the compressive strengths at 7, 28, 56 and 91 days. For each testing age, three specimens were prepared and the average result was taken.

### 4.5.3 Results and discussions

**(1) Results for fresh concrete**

Table 4.7 shows the test results for fresh concrete. The $V_w/V_p$ values applied to the test are the target values estimated in the mortar test. The *Sp/P* values applied were adjusted to obtain a proper slump flow value=650 ± 50 mm. However, in the case of mix No.10, the slump flow could not reach 600 mm even though a high amount of superplasticizer was dosed compared to the other cases.

The results for the V funnel time were well controlled at 13 ± 3 sec except for the mixes No. 1 and 15. Mix No. 1 resulted in a more viscous mixture than was expected, but the deviation was not so large. The V funnel time of mix No. 15 was slightly longer than the control value due to the relatively small slump flow. If the slump flow is increased by a larger dosage of superplasticizer, the V funnel time shifts to the control range. Therefore, it is considered that the results obtained in this experiment prove the appropriateness of the applied $V_w/V_p$ values which are estimated by the mortar tests for realizing an adequate balance of flowability and viscosity of the mixtures.

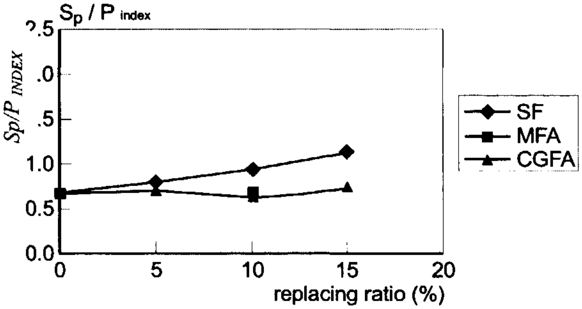
The criterion of the box test, the filling height $\geq$ 300 mm, was fulfilled in all the cases. This means that the mixtures examined in this experiment have enough passing-through ability as SCC.

The filling ratios of the filling vessel test showed very high percentages for all the mixtures tested. Only the mixes No. 5, 10 and 15 could not reach the target criterion of 90%. These three mixtures have a common tendency for the slump flow value which is smaller than 625 mm. Therefore, they can be redesigned to modify the filling ratio of these mixtures by an additional dosage of the superplasticizer to increase the slump flow value.

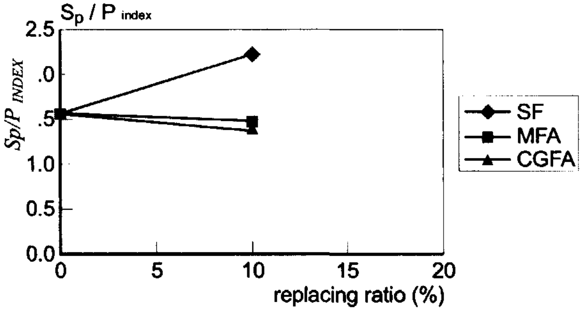
On the basis of the test results mentioned before, it can be concluded that the application of the $V_w/V_p$ values determined in the mortar tests are quite adequate to produce SCC even when different types of basic powder compositions and different types of microfillers are used. However, there is one aspect to be noticed. According to the results shown above, it seems to be true that all mixtures behave equally as fresh concrete when the slump flow and the V funnel time, in other words the deformability and the viscosity, are controlled at the target values adjusting the values of $V_w/V_p$ and *Sp/P* for different powder compositions. This is almost correct for the mixtures examined in this study. However, some mixtures showed a heavier handling-ability than other mixtures in spite of the controlled slump flow and V funnel time. For example, the powder composition BSC 50% + PC 50% showed such a tendency typically, and

Table 4.7 Test cases and results for fresh concrete

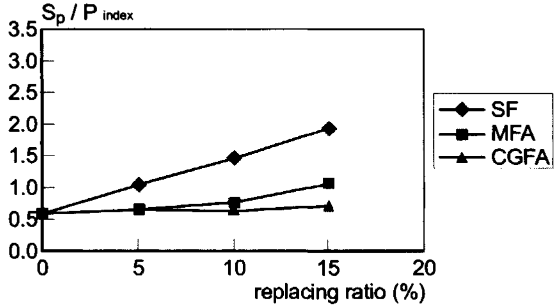
| mix No. | powder composition (% in volume) | $V_w/V_p$ | *Sp/P* (%) | slump flow (mm) | V funnel Time (sec) | Box test Hb (mm) | Filling vessel H (mm) | Filling vessel F (%) | slump flow after test (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | BSC 100% | 0.815 | 0.700 | 675.00 | 19.25 | 329 | 10 | 98.1 | 720.00 |
| 2 | BSC 90% + MFA 10% | 0.805 | 0.660 | 647.50 | 12.60 | 328 | 25 | 95.2 | 665.00 |
| 3 | BSC 95% + SF 5% | 0.750 | 0.820 | 670.00 | 14.30 | 331 | 14 | 97.4 | 697.50 |
| 4 | BSC 95% + SF 10% | 0.710 | 0.950 | 667.50 | 15.30 | 330 | 15 | 96.9 | 665.00 |
| 5 | BSC 95% + SF 15% | 0.675 | 1.050 | 605.00 | 15.05 | 323 | 58 | 88.7 | 610.00 |
| 6 | BSC 95% + CGFA 5% | 0.765 | 0.710 | 652.50 | 13.65 | 330 | 16 | 96.9 | 697.50 |
| 7 | BSC 95% + CGFA 10% | 0.715 | 0.650 | 662.50 | 14.05 | 330 | 15 | 97.1 | 692.50 |
| 8 | BSC 95% + CGFA 15% | 0.660 | 0.740 | 650.00 | 15.25 | 328 | 30 | 94.0 | 660.00 |
| 9 | BSC 50% + PC 50% | 0.835 | 1.500 | 627.50 | 12.35 | 324 | 46 | 91.3 | 630.00 |
| 10 | BSC 45% + PC 45% + SF 10% | 0.750 | 2.000 | 587.50 | 13.90 | 314 | 65 | 86.9 | 592.50 |
| 11 | BSC 45% + PC 45% + MFA 10% | 0.825 | 1.450 | 642.50 | 13.50 | 316 | 45 | 91.1 | 635.00 |
| 12 | BSC 45% + PC 45% + CGFA 10% | 0.765 | 1.420 | 670.00 | 11.70 | 329 | 24 | 95.3 | 640.00 |
| 13 | BSC 60% + FA 40% | 0.725 | 0.820 | 665.00 | 14.05 | 330 | 13 | 97.5 | 685.00 |
| 14 | BSC 60% + FA 30% + SF 10% | 0.655 | 1.400 | 677.50 | 13.80 | 329 | 12 | 97.7 | 680.00 |
| 15 | BSC 60% + FA 30% + MFA 10% | 0.730 | 0.820 | 622.50 | 16.05 | 325 | 55 | 89.0 | 617.50 |
| 16 | BSC 60% + FA 30% + CGFA 10% | 0.650 | 0.800 | 695.00 | 12.75 | 333 | 15 | 97.0 | 697.50 |



(a) basic powder: BSC 100%



(b) basic powder: BSC 50% + PC 50%



(c) basic powder: BSC 60%+FA 40%

Figure 4.8 Influence of microfillers on dosage of superplasticizer in concrete

the handling-ability can be improved when a microfiller, especially CGFA, is applied. This phenomenon can not to be evaluated on basis of the testing data taken in this experimental program, but the handling-ability is one of the very important factors to govern the workability of the fresh concrete. This means that the testing methods applied in this study are not always sufficient to evaluate the workability of SCC quantitatively.

In order to estimate the appropriate dosage of superplasticizer for each powder composition under the application of the $V_w/V_p$ obtained by the mortar test, the following index is introduced:

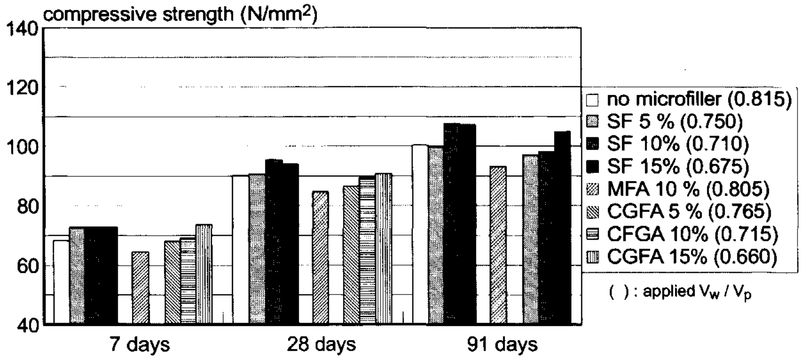
$$Sp/P_{INDEX} = (Sp/P_{APPLIED}) \cdot \left( \frac{650}{SlumpFlow} \right) \qquad (3.2)$$

Figure 4.8(a) shows the variation of $Sp/P_{INDEX}$ as a function of the type and the replacing percentage of the microfillers when applying the basic powder composition of BSC100%. It is clear from this figure that an increase of the replacing percentage of SF causes a linear increase of the $Sp/P_{INDEX}$, whereas MFA and CGFA do not increase the $Sp/P_{INDEX}$. This is the same tendency as shown by the result of the mortar tests as can be seen in the Figures 4.5(a)-(c). Figures 4.8(b) and (c) show the variation of $Sp/P_{INDEX}$ due to the type of the microfillers when applying the basic powder compositions BSC50%+PC50% and BSC60%+FA40% respectively. In both figures, the application of SF resulted in a higher value of the $Sp/P_{INDEX}$ than for the original basic powder compositions and other type of microfillers, MFA and CGFA. In the case of CGFA, the $Sp/P_{INDEX}$ is even lower than for the original basic powder compositions when the replacing percentage is 10%. From this result, it can be concluded that the application of SF is less economical than the MFA and the CGFA concerning the fresh properties of SCC.

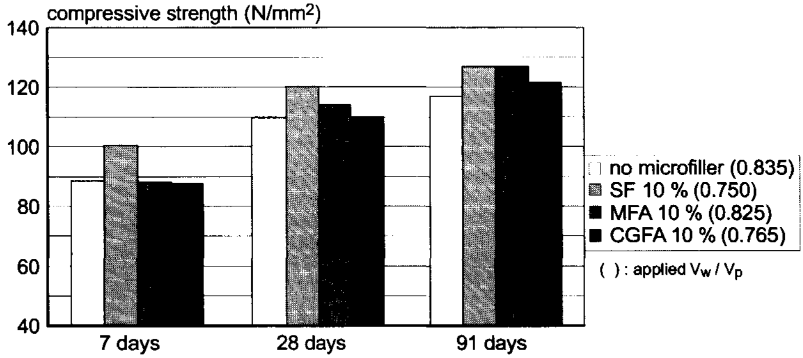
### (2) Results for the compressive strength

Figures 4.9(a)-(c) show the test results for the compressive strength for the concretes mixed in this experimental series. The tests were conducted at 7, 28 and 91 days after mixing on cubes (150×150×150 mm).

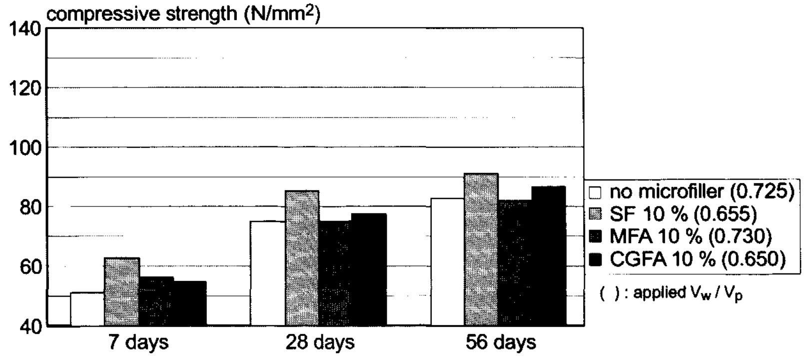
Figure 4.9(a) shows the strength development of the mixtures whose basic powder composition was BSC 100%, and SF, MFA or CGFA was applied with different replacing percentages. The application of SF enhanced the compressive strength more than MFA and CGFA. 10 % replacement by SF resulted in the highest strength among the mixtures shown in Figure 4.9(a) at



(a) basic powder: BSC 100%



(b) basic powder: BSC 50%+PC 50%



(c) basic powder: BSC 60%+FA 40%

Figure 4.9 Influence of microfillers on compressive strength of concrete

28 and 91days. 10 % replacement by MFA showed a reduction of the compressive strength at all ages compared to the mixtures without microfiller. The use of CGFA hardly influenced the strength at a relatively small dosage in spite of the reduction of $V_w/V_p$. When applying 15 % replacement, an enhancement of the compressive strength was observed due to substantial reduction of $V_w/V_p$. These tendencies mentioned above nearly correspond to the results of the mortar tests shown in Figure 4.6(a).

Figure 4.9(b) shows the strength development of the mixtures whose basic powder composition is BSC 50% + PC 50%, and SF, MFA or CGFA was applied with 10% replacement. The use of SF increased the strength most among the microfillers applied. CGFA hardly enhanced the strength at any age. The use of MFA resulted in a better strength development than CGFA in spite of a higher value of $V_w/V_p$. These results correspond well with the results of the mortar tests shown in Figure 4.6(b). In this case, all the mixtures with or without different kinds of microfillers had a compressive strength higher than 100 N/mm$^2$ at 28 days.

Figure 4.9(c) shows the strength development of the mixtures whose basic powder composition is BSC 60% + FA 40%, and when SF, MFA or CGFA was applied with 10% replacing FA. The use of SF increased the compressive strength as well as in the other cases. On the other hand, the use of MFA and CGFA showed only little enhancement of the strength development. In the mortar tests, the use of MFA and CGFA partially replacing the normal fly ash (FA) obtained a particular increase of the compressive strength (see Figure 4.6(c)). However, the effect was cut down in the concrete test.

## 4.6 CONCLUSIONS

The utilization of microfillers, silica fume, micronized fly ash and coal gasification fly ash, for high strength self-compacting concrete with a strength higher than 100 N/mm$^2$ after 28 days was studied experimentally. According to the test results described above, the following conclusions can be drawn:

(1) The silica fume (SF) and the coal gasification fly ash (CGFA) applied in this study can substantially reduce the viscosity of the fresh concrete when the water to powder volume ratio ($V_w/V_p$) is constant. As a consequence of this effect, the application of SF and CGFA results in a lower $V_w/V_p$, necessary to realize the particular viscosity of fresh concrete mixtures as a workable SCC than for SCC without these microfillers. On the other hand, the micronized fly ash (MFA) does not perform in such a way.

(2) The application of SF tends to spoil the deformability (slump flow value) of a fresh concrete mixture. Therefore, a high amount of superplasticizer is required to obtain a proper deformability as a SCC. On the other hand, the use of MFA and CGFA does not increase the dosage of the superplasticizer necessary to give a particular deformability.

(3) For an enhancement of the compressive strength, SF is the best material among the three microfillers tested in this study. MF and CGFA do not increase, sometimes decrease, the compressive strength when they are applied to SCC mixtures.

According to the conclusions (1) and (2), the CGFA can be considered as a very suitable material to enhance the workability of SCC. In chapter 5, the effect of SF to enhance the workability of SCC when it is too viscous and heavy to handle due to the too low mixing efficiency of the mixer available will be pointed out. For such a case, the application of CGFA is possibly more reasonable than that of SF because it does not require an extra dosage of superplasticizer.

From the point of view of strength development, SF can be considered as the best material among them. However, the application of SF is not always necessary in order to realize a strength of 100 N/mm$^2$ after 28 days, because some basic powder compositions, e.g. BSC50%+PC50%, already result in such a level of strength with sufficient self compactability. However, the use of the microfillers, especially SF and CGFA, can enhance the handling-ability of high strength SCC in the fresh state very well. This effect cannot be properly evaluated by the test results quantitatively obtained in this study. Therefore, the use of SF or CGFA is recommendable considering the practical application of high strength SCC.

# CHAPTER 5
# INFLUENCE OF MIXING EFFICIENCY AND ADMIXTURES ON THE PROPERTIES OF FRESH SCC

## 5.1 INTRODUCTION

### 5.1.1 Background of this chapter

In Chapter 3, the application of a mixture proportioning system for SCC recommended by *Okamura* et al. [8] was reported verifying the producibility of SCC in The Netherlands. This method is called the "general purpose approach" and aims at designing self compactability of fresh concrete reliably for general purpose applications with both satisfactory mechanical properties and durability of the concrete also in the hardened state.

Through a substantial number of concrete mixing tests, it was confirmed that the general purpose approach is fundamentally applicable to Dutch materials and SCC is reliably producible in the Netherlands. A recommendation was made for the materials and the proportioning parameters to obtain the SCC NL-Prototype in Chapter 3. However, it was also found through the experiments that the general purpose approach should be modified to be more suitable to Dutch conditions, especially concerning the mixing of concrete.

In the designing system for general purpose SCC, the concrete is required to be mixed by a forced mixer, preferably a pugmill type forced mixer which has horizontal dual axes. It was concluded that a gravity mixer is not suitable to produce SCC because it takes quite a long mixing time to disperse the powder particles sufficiently in the concrete [8]. This means that if a concrete is designed by the general purpose approach, and is mixed by a gravity mixer for a common mixing time, the concrete cannot be workable at all. SCC needs a more intensive mixer.

However, a gravity tilting mixer is commonly and practically used in the Dutch ready-mixed concrete industry and the number of pugmil type mixers is not large. Especially, there are no laboratory-scale pugmil mixers in the Netherlands. The gravity tilting mixers are quite commonly used also in the laboratories. Therefore, it is necessary for popularization of SCC in the Netherlands to make it producible by this gravity tilting mixer.

Moreover, as described in Chapter 1, the mixture designing process of SCC still, always, includes trial-and-error steps even in Japan and the results in the laboratory mixing test more or less deviate from the results of practical mixing, which means that additional adjustments are necessary to produce SCC by an industrial concrete plant. Therefore, the author thinks that there are still some open questions in the SCC technology and one of the main reasons of this situation is a lack of knowledge on the influence of mixing, the influence of chemical admixtures and the mutual relation between them.

### 5.1.2 Purpose of this chapter

In this chapter, the influence of the mixing efficiency on the proportioning of defined properties of fresh SCC is investigated. A number of concrete mixing tests are conducted with varying mixing procedures and types of mixers in order to clarify the existence of the problem concerning the mixing efficiency for the SCC production. Furthermore, it is tried to establish a hypothesis for the effect of mixing on the properties of fresh SCC to understand what happens in concrete during mixing. The result and conclusion of this chapter is expected to show the necessity for a more specific study on the influence of the mixing and to be the introduction of the next chapter.

## 5.2 CHARACTERISTICS OF THE APPLIED MATERIALS

### 5.2.1 Powder materials

Table 5.1 shows the characteristics of the applied cement and fly ash. BSC is a Dutch common blast furnace slag cement. FA1 and FA2 are from the same brand of fly ash, but the delivery dates are different.

Table 5.1 Characteristics of the powder materials

| Powder name | Specific gravity | Blaine ($m^2/kg$) | $\beta_p$ | $E_p$ | Clinker (%) | Slag (%) | Fly ash (%) |
|---|---|---|---|---|---|---|---|
| Blast furnace slag cement (BSC) | 2.94 | 381 | 0.924 | 0.0869 | 21.8 | 70.3 | 3.3 |
| Fly ash (FA1) | 2.33 | 277 | 0.726 | 0.0435 | - | - | 100 |
| Fly ash (FA2) | 2.31 | 328 | 0.824 | 0.0389 | - | - | 100 |
| BSC 60%+FA1 40% | - | - | 0.864 | 0.0623 | - | - | - |
| BSC 60%+FA2 40% | - | - | 0.874 | 0.0727 | - | - | - |
| Silica fume (SF) | 2.20 | *0.15μm | - | - | - | - | - |

*average particle size

Silica fume (SF) was used in some cases to improve the workability of heavily viscous mixtures. The properties of the dry substances are also shown in Table 5.1, but the SF was actually supplied as a slurry (50% weight concentration in water).

The combination of BSC60% and FA40% in volume is the standard powder composition in the recommendation of the SCC NL-Prototype. In this chapter, the experimental results with this powder composition are mainly discussed, and in some cases SF is added.

### 5.2.2 Chemical admixtures

Table 5.2 shows the characteristics of the applied superplasticizers. SP-A and B are the superplasticizers of polycarboxylic ether complex. SP-C is a naphthalene sulfonate based one. All of them are products from the Dutch market. SP-B has a similar active polymer as SP-A but the initial dispersibility is lower than A. However, SP-B has a better ability for slump retention. In order to obtain a sufficient stability of the mixture during the test, SP-A and B are used together in a combining ratio of 1:2.5 in weight. SP-C does not have enough ability for flowability retention, but a sufficient initial dispersibility for the powder composition applied.

Welan gum was used as a viscosity modifying admixture in this research. The dosage of welan gum was fixed at 0.05% of the water weight when it was applied.

Table 5.2 Characteristics of the superplasticizers

| | Product name | Chemical description | Specific gravity* | Solid concentration (%) |
|---|---|---|---|---|
| SP-A | Glenium 51 | Polycarboxylic ether complex | 1.10 | 35 |
| SP-B | Glenium 27 | Polycarboxylic ether complex | 1.05 | 20 |
| SP-C | Betomix 415+O | Naphthalene sulfonate | 1.21 | 39 |

*solution base

### 5.2.3 Aggregate

Table 5.3 shows the characteristics of the fine and the coarse aggregate used. These are typical Dutch river sand and river gravel aggregates. The maximum size of the gravel is 16 mm. The border size between fine and coarse aggregate, the maximum size of the sand, is 4 mm according to the Dutch standard.

In the general purpose approach, the particles finer than 0.09 mm in the fine aggregate are not considered as aggregates, but as powders. In this investigation, 0.125 mm is considered as the limit between the aggregate and the powder because of the sieve size of the Dutch standard.

## 5.3 EXPERIMENTAL PROGRAM

### 5.3.1 Tests on mortar

To determine the adequate value of $V_w/V_p$ according to the general purpose approach, mortar tests were performed. Mortars were mixed by a Hobart mixer through the procedure shown in Figure 5.1. The first mixing water to powder volume ratio is estimated to be 0.7 times the $\beta_p$ of the powder composition applied. The volume of the mortar mixed was two liters for each batch. The volume fraction of the fine aggregate (>0.125 mm) in the mortar, $S_c/M$, was fixed at 40%. The moisture condition of the fine aggregate was controlled at the saturated surface dry condition. After the mixing, the mortar flow test (see Figure 2.30) and the mortar funnel test (see Figure 2.31) were executed. Each test was performed twice in sequence and the mean value was considered to be representative for each mixture. The dosage of superplasticizer was adjusted in order to obtain the proper flowability ($\Gamma_m$=5).

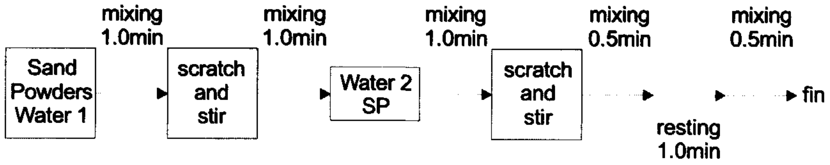


Figure 5.1 Mixing procedure of mortar

The value of $V_w/V_p$, which realizes $\Gamma_m$=5 and $R_m$=1 simultaneously, was determined for the following three combinations of powder composition and chemical admixtures:

(a)BSC:60%&FA1:40%+SP-A&B
(b)BSC:60%&FA2:40%+SP-A&B+welan gum
(c)BSC:60%&FA2:40%+SP-C

The value of $V_w/V_p$ obtained from this test is defined as the adequate $V_w/V_p$ for SCC according to the general purpose approach. The adequate values of $V_w/V_p$ are denoted as $\gamma_a$, $\gamma_b$ and $\gamma_c$ for the combinations (a), (b) and (c) respectively.

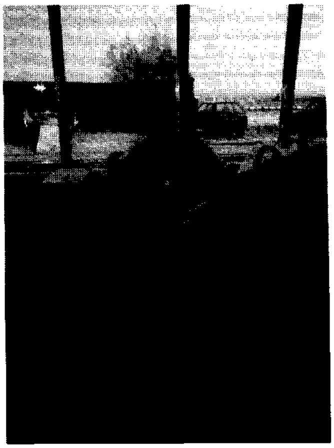
### 5.3.2 Tests on concrete

#### (1) General

A number of concrete mixing tests were carried out to evaluate the influence of the mixing efficiency on the properties of fresh concrete. The volumes of coarse and fine aggregate were constant throughout the whole program, with $G/G_{lim}$=55% and $S_c/M$=40%. This means that the volume fractions of aggregate and paste were fixed for all mixtures. The moisture condition of the fine and the coarse aggregate was controlled at wet (water content was around 2 %) and the amount of mixing water was adjusted according to the amount of surface moisture of the aggregates. Variables in this test series were $V_w/V_p$, Sp/P and the mixing intensity. The mixing intensity was studied by varying the mixer types and the mixing durations.

#### (2) Mixer

In this experiment, two types of mixers were used to produce SCC. One is a forced pan mixer (F-mixer) shown in Picture 3.4, and another is a gravity tilting mixer (G-mixer) shown in Picture 5.1. The details of the F-mixer are described in 3.4.4. The drum of the G-mixer has an inner diameter of 600 mm at largest. The drum turns at 20 rpm.



Picture 5.1 Gravity tilting mixer

**(3) Mixing Procedure**

Figure 5.2 shows the six different mixing ways which were applied to the concrete production. They are denoted as F5.0, F3.5, G7.5, G5.5, G3.5 and G2.5 respectively according to the mixer type and the total mixing time in minutes. The mixing intensity is regarded to be bigger in this order. The volume of concrete mixed was 45 liters for each batch. In the following series A and B, two batches of concrete were mixed in sequence for one mixture, and they were combined together and tested. In series C and D, only one batch of concrete was mixed for one mixture.

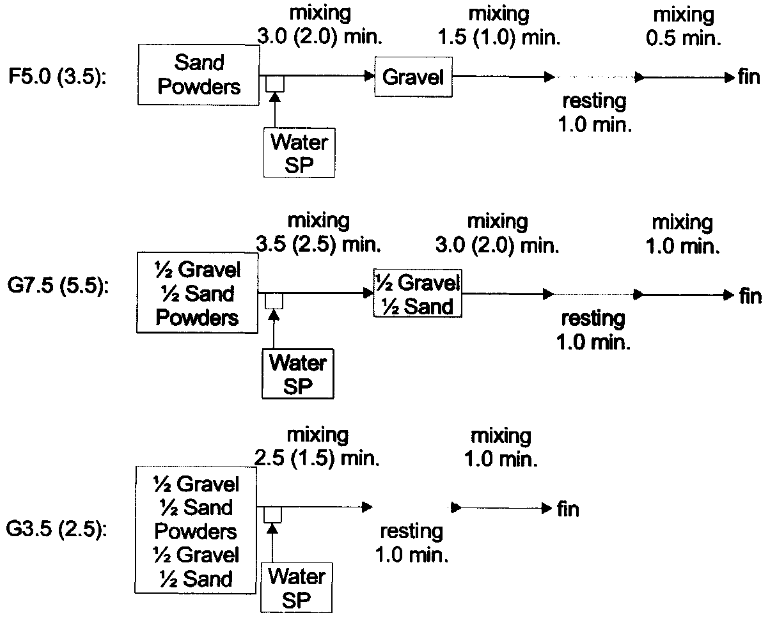


Figure 5.2 Mixing procedures for concrete

The test program on concrete was subdivided into 3 series according to the applied material combination mentioned above, and another additional series.

**(4) Series A**

Concretes with material combination "(a) BSC:60%&FA1:40%+SP-A&B" were mixed in the six different mixing ways shown in Figure 5.2. The ratio $V_w/V_p$ was varied as $\gamma_a \times \alpha$ ($\alpha \geq 1.0$) to make the properties of the concrete appropriate for SCC. For all mixtures, the slump flow test (see Figure 2.17) and the V funnel test (see Figure 2.18) were carried out. The ratio Sp/P was adjusted to obtain a proper deformability (slump flow value). In this experiment, a slump flow value=650±30mm and a V funnel time=11±2sec were considered as the most adequate values for a workable SCC. In the tests of Series A, the box test (see Figure 2.24 and 2.25) [20] and the filling vessel test (see Figure 2.21) [22] were conducted to evaluate the self compactability of the concretes mixed. For these tests, the following values are regarded as sufficient to qualify the concrete as self compactable: (a) The filling height of the box test is larger than 300mm. (b) The filling ratio in the filling vessel test, F, is higher than 90%. In this series, the polycarboxylic ether type of superplasticizer was used and the influence of mixing was studied in most detail.

**(5) Series B**

Concretes with material combination "(b) BSC:60%&FA2:40%+SP-A&B+welan gum" were mixed in four different mixing ways, F5.0, F3.5, G7.5 and G3.5. The ratio $V_w/V_p$ was varied as $\gamma_b \times \alpha$ ($\alpha \geq 1.0$) to make the properties of the concrete appropriate for SCC. The ratio Sp/P was adjusted to obtain a proper deformability. The slump flow test and the V funnel test were performed for all mixtures, and the box test and the filling vessel test were executed for some mixtures. In this series, it was studied whether the addition of welan gum influenced the sensitivity of the mixtures for the mixing efficiency. Series A was used as a reference.

**(6) Series C**

Concretes with material combination "(c) BSC:60%&FA2:40%+SP-C" were mixed in four different mixing ways, F5.0, F3.5, G7.5 and G3.5. The ratio $V_w/V_p$ was varied as $\gamma_c \times \alpha$ ($\alpha \geq 1.0$) to make the properties of the concrete appropriate for SCC. The ratio Sp/P was adjusted in order to obtain a proper deformability. The slump flow test and the V funnel test were carried our for all mixtures. The box test and the filling vessel test were not executed because the applied superplasticizer did not have a sufficient ability for flowability retention and it might cause "flow loss" during the tests. Therefore, as a condition it was assumed that the self compactability of the concrete was sufficient just after mixing when a slump flow value=650±30mm and a V funnel time=11±2sec were obtained. In this series, it was studied whether the use of a naphthalene type superplasticizer showed a different sensitivity of the mixture for the mixing efficiency. Also here the series A was used as a reference.

**(7) Series D**

In order to evaluate the influence of the mixing efficiency more clearly, three batches of concrete were mixed according to three different mixing procedures, F5.0, F3.5 and G7.5, with completely the same mix proportion in which $V_w/V_p$ and Sp/P were fixed at the adequate values for the mixing procedure F3.5. For this experiment, a powder composition with "BSC:60%&FA2:40%" was applied. In addition, another powder composition with "BSC:60%&FA2:37%&SF:3%" was applied to mixing procedure G7.5 with the same values of $V_w/V_p$ and Sp/P as in the previous cases, in order to compare the influences of the mixing intensity and the existence of a microfiller in the SCC mixture. For each case, one batch of concrete was mixed in a volume of 45 liters. After mixing, the slump flow test and the V funnel test were executed and the unit weight of each mixture was determined in order to evaluate the air content. The compressive strengths of the concretes were determined at 7 and 28 days.

## 5.4 RESULTS AND DISCUSSIONS

### 5.4.1 Results of tests on mortar

The most adequate values of water to powder volume ratio, $\gamma_a$, $\gamma_b$ and $\gamma_c$ for the material combinations (a), (b) and (c) respectively were established by the mortar flow and the funnel test. The values obtained were $\gamma_a=0.765$, $\gamma_b=0.805$ and $\gamma_c=0.840$.

### 5.4.2 Results and discussions of tests on concrete: Series A

**(1) General**

Table 5.3 shows the mixture parameters and results of the slump flow and V funnel test of the 10 mixtures tested in this series. Most of the mixtures resulted in the target values of the slump flow (650 ± 30 mm) and the V funnel time (11 ± 2 sec.) except the mixtures A2, A5 and A6. Most of them demonstrated high self compactability in the box test ($B_h \geq 300$ mm) and the filling vessel test ($F \geq 90$ %) except only the mixture A6 (F= 89 %). However, some of them were not workable because of a too high viscosity and heavy handling resistance in spite of sufficient deformability and high self compactability.

**(2) Influence of mixing time by forced mixer**

The concretes A1-A4 were mixed by the forced pan mixer with different combinations of mixing time and $V_w/V_p$. The slump flow of each mixture was adjusted at 650±30mm by adjusting the dosage of superplasticizer. The result showed that the $V_w/V_p$ estimated by the mortar test, $\gamma_a=0.765$, is a quite adequate value for the mixing procedure F5.0, because it (mixture A1) resulted in a proper V funnel time and good self compactability when the slump flow value was controlled around 650 mm. On the other hand, when a concrete (mixture A2) is mixed by mixing procedure F3.5, $\gamma_a$=0.765 resulted in a longer V funnel time than the proper value, and the mixture A4 with $V_w/V_p$ = 0.803 (= $\gamma_a$ ×1.05) showed the target V funnel time and a higher self compactability than mixture A2. When the $V_w/V_p$= $\gamma_a$ ×1.05 is applied to mixing procedure F5.0 (mixture A3), the V funnel time is shorter than for mixture A1, and this means that the

Table 5.3 Mixture parameter and results in Series A

| Mix No. | α | Mixing | $V_w/V_p$ | Sp/P (%) | Slump flow (after mix) (mm) | V funnel time (sec) | Slump flow (after test) (mm) |
|---|---|---|---|---|---|---|---|
| A1 | 1.000 | F5.0 | 0.765 | 0.570 | 657.5 | 11.05 | 662.5 |
| A2 | | F3.5 | | 0.565 | 622.5 | 16.00** | 665.0 |
| A3 | 1.050 | F5.0 | 0.803 | 0.540 | 670.0 | 9.80 | 675.5 |
| A4 | | F3.5 | | 0.520 | 655.0 | 10.55 | 672.5 |
| A5 | | G7.5 | | 0.470 | 745.0** | 26.90** | 745.0 |
| A6* | | | | 0.410 | 650.0 | 35.50** | 630.0 |
| A7 | 1.120 | | 0.858 | 0.368 | 652.5 | 11.55 | 640.0 |
| A8 | 1.140 | G5.5 | 0.872 | 0.360 | 647.5 | 11.35 | 640.0 |
| A9 | 1.175 | G3.5 | 0.899 | 0.360 | 622.5 | 9.80 | 630.0 |
| A10 | | G2.5 | | 0.375 | 657.5 | 9.05 | 660.0 |

*: insufficient self compactability

**: out of the target

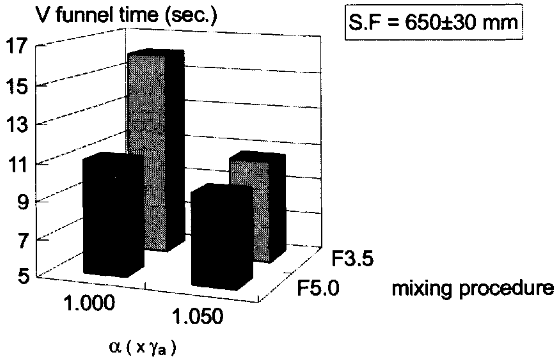


Figure 5.3 Influence of mixing time by F-mixer

viscosity, in other words segregation resistance, of this concrete is lower than that of mixture A1. Figure 5.3 shows this tendency graphically.

### (3) Influence of mixer type

The concretes A3-A6 were mixed with the same $V_w/V_p$ of 0.803 (=$\gamma_a \times 1.05$) but by different mixers. The mixtures A3 and A4 were mixed by the forced pan mixer, and A5 and A6 were mixed by the gravity tilting mixer. As explained before, the mixtures A3 and A4 had a high self-compactability and good workability, although A3 was less viscous than A4. On the other hand, the mixtures A5 and A6 resulted in very long V funnel times, and the handling resistance of both concretes was very high, so that these concretes can be qualified as "unworkable concretes". In Figure 5.4, it can be seen that the V funnel time is significantly changed due to the difference of mixer type when $V_w/V_p$ is constant and the slump flow value is controlled.

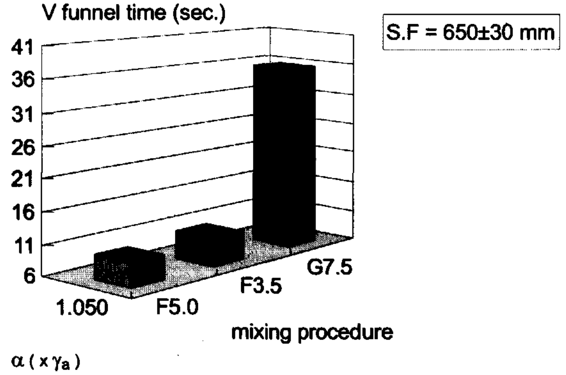


Figure 5.4 Influence of mixing procedure on V funnel time

The most adequate dosage of superplasticizer was also drastically influenced by the type of mixer (see Figure 5.5). The mixture A6 had the same $V_w/V_p$ and slump flow value as mixture A4, but it required a 21% smaller amount of superplasticizer than A4.

Moreover, from the results of these mixtures, another remarkable fact appeared. As explained before, the mixtures A5 and A6 were too viscous and extremely unworkable. However, they showed a high self-compactability in the box test and the filling vessel test. Especially the mixture A5 resulted in the highest filling height and the highest filling ratio among all the mixtures tested. Actually, the mixture A5 had a very high deformability (higher than the control range) and a very high segregation resistance (much more viscous than the control range):

therefore it should principally be qualified as having a very high self-compactability according to the definition and mechanism of the self-compactability explained so far. This result proves that self-compactability can be realized when the concrete has a high deformability and a high segregation resistance even though the concrete is not workable.

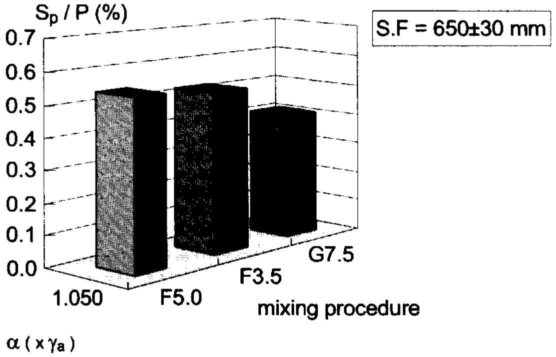


Figure 5.5 Influence of mixing procedure on Sp/P

### (4) Influence of mixing time by gravity tilting mixer

The concretes A7-A10 were mixed by the gravity tilting mixer with different combinations of mixing time and $V_w/V_p$. The slump flow of each mixture was adjusted at 650 ± 30 mm by adjusting the dosage of superplasticizer. The $V_w/V_p$ of each mixture was adjusted to make the V funnel time result in 11 ± 2 sec.

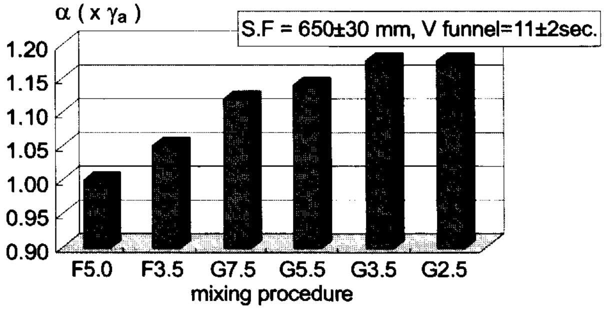


Figure 5.6 Influence of mixing procedure on optimized $V_w/V_p$

Figure 5.6 shows the relation between the water to powder volume ratio (premium factor $\alpha$) and the mixing time. Short mixing requires a high $V_w/V_p$ ($\alpha$) to obtain the adequate V funnel time. However, mixing procedures G3.5 and G2.5 seem to require almost the same value of $V_w/V_p$. This implies that an upper limit of the water to powder volume ratio exists for a material combination independent of the mixing efficiency. The mixing procedure G2.5 represents the lower limit of the mixing by the mixer used to produce a homogeneous mixture.

Figure 5.7 shows the relation between the dosage of superplasticizer and the mixing intensity (time) when the slump flow and V funnel time are controlled at 650 ± 30 mm and 11 ± 2 sec. respectively. In the case of mixing by the G-mixer, 0.35-0.40 % of Sp/P was adequate for all mixtures tested. However, shorter mixing tends to require a bit more plasticizer when $V_w/V_p$ is the same. This result is contrary to the result obtained by the F-mixer.

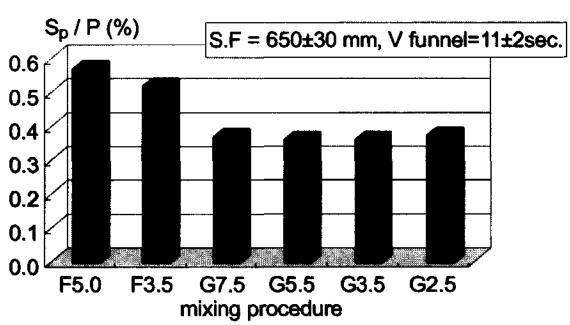


Figure 5.7 Influence of mixing procedure on optimized Sp/P

**(6) Evaluation of adequate $V_w/V_p$ and Sp/P for each mixing intensity**

From the results noted above, adequate values of $V_w/V_p$ and Sp/P can be expected for each mixing procedure when applying material combination (a). Figures 5.5 and 5.6 show the relation between the optimized values of $V_w/V_p$, Sp/P and the mixing procedures. In order to produce a concrete with the same slump flow and the same V funnel time, so the same self compactability, the different mixing intensities require different values of $V_w/V_p$ and Sp/P even when materials of the same quality are used. The forced pan mixer needs more superplasticizer and a lower water to powder volume ratio than the gravity tilting mixer. In other words, the gravity tilting mixer requires a smaller amount of superplasticizer and a smaller amount of powder (binder) materials to produce the same fresh-quality of self-compacting concrete.

### 5.4.3 Results and discussions for tests on concrete: Series B

Table 5.4 shows the mixture parameters and results of the slump flow and V funnel test of the 6 mixtures tested in this series. They were mixed with different mixing procedures and $V_w/V_p$ with the material combination (b) "BSC:60%&FA2:40%+SP-A&B+welan gum". Most of the mixtures resulted in nearly the target values of the slump flow (650 ± 30 mm) and the V funnel time (11 ± 2 sec.) except the mixture B2 which showed a much longer V funnel time than the target value.

From this result, the $V_w/V_p$ estimated by the mortar test, $\gamma_b$=0.805, can be concluded as a quite adequate value for the mixing F5.0 in the same way as for series A. However, in the case of mixture B2, which was mixed by the mixing procedure F3.5 with $\alpha$=1.00, the V funnel time was longer (the viscosity was higher) than for mixture A2 which was mixed with the same premium factor $\alpha$=1.00.

Table 5.4 Mixture parameter and results in Series B

| Mix No. | $\alpha$ | Mixing | $V_w/V_p$ | Sp/P (%) | Slump flow (after mix) (mm) | V funnel time (sec) | Slump flow (after test) (mm) |
|---|---|---|---|---|---|---|---|
| B1 | 1.000 | F5.0 | 0.805 | 0.670 | 660.0 | 11.70 | 675.0 |
| B2 | | F3.5 | | 0.650 | 607.5** | 21.15** | 637.5 |
| B3 | 1.050 | | 0.845 | 0.550 | 632.5 | 13.10** | 640.0 |
| B4 | 1.070 | | 0.865 | 0.530 | 635.0 | 10.70 | 647.5 |
| B5 | 1.120 | G7.5 | 0.906 | 0.500 | 615.0** | 15.45** | 675.5 |
| B6 | 1.175 | G3.5 | 0.946 | 0.550 | 570.0** | 13.15** | 637.5 |

**: out of the target

In series A, $\alpha$=1.05, 1.12 and 1.175 are the nearly adequate premium factors of $V_w/V_p$ for the mixing procedures F3.5, G7.5 and G3.5 respectively (see Table 5.3). In the series B, these premium factors resulted in a more viscous concrete compared to the case of series A. Figure 5.8 shows the phenomena in a diagram. This fact implies that a concrete including welan gum has a tendency to be more viscous than a concrete without welan gum if the mixing is not sufficient. In other words, a welan-gum concrete needs a larger increase of $V_w/V_p$ than a non-welan-gum concrete to generate the same workability when the mixing becomes less intensive.

This tendency agrees with the "property stabilizing effect" of this material. Welan gum has an ability to reduce the variation of the properties of fresh concrete due to a variation of $V_w/V_p$ compared to a concrete without welan gum. In other words, it requires a larger change of $V_w/V_p$ to adjust the fresh properties varied by the other reason, e.g. the mixing intensity.

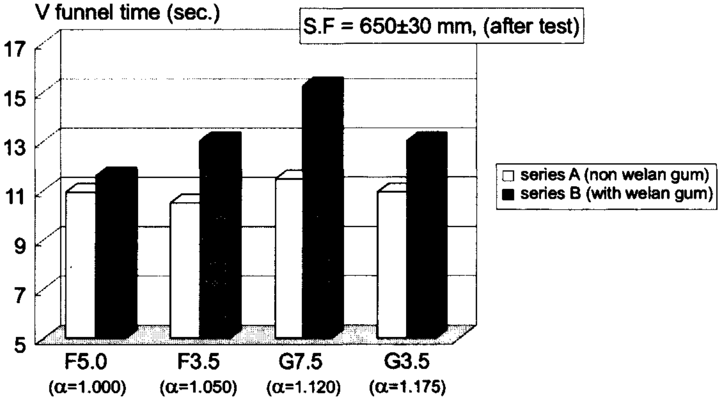


Figure 5.8 Influence of welan gum on premium factor α

In the case of mixtures B5 and B6 which were mixed by the gravity tilting mixer, the initial flowability was not sufficient and it increased in dependence of the time. This tendency was not observed in the series A (see Table 5.3). This behavior implies that the welan-gum concrete requires to be mixed more intensively to show stable flowability from the initial stage.

### 5.4.4 Results and discussions for tests on concrete: Series C

Table 5.5 shows the mixture parameters and results of the slump flow and V funnel test for 8 mixtures tested in this series. They were mixed with different combinations of mixing procedure and $V_w/V_p$ with the material combination (c) "BSC:60%&FA2:40%+SP-C". SP-C is a superplasticizer based on naphthalene sulfonate.

The mixture C1 which was mixed with the $V_w/V_p$ estimated by the mortar test, $\gamma_c$=0.830, resulted in a bit more viscous concrete than the target property. However, the mixture C4 with α=1.05, which was mixed by mixing procedure F5.0 as well as C1, resulted in a too short V funnel time. Therefore, the most adequate value of α for the mixing procedure F5.0 should lie between 1.00 and 1.05, and α=1.03 seems to be adequate. On the other hand, α=1.10 is slightly low as the adequate value for mixing procedure G3.5 because it resulted in a longer V funnel time than the target value. α=1.12 seems to be adequate.

Table 5.5 Mixture parameters and results for series C

| Mix No. | α | Mixing | $V_w/V_p$ | Sp/P (%) | Slump flow (after mix) (mm) | V funnel time (sec) |
|---|---|---|---|---|---|---|
| C1 | 1.000 | F5.0 | 0.830 | 1.250 | 635.0 | **14.45**** |
| C2 | | F3.5 | | 1.250 | **722.5**** | **16.25**** |
| C3 | | | | 1.170 | **685.0**** | **18.05**** |
| C4 | 1.050 | F5.0 | 0.872 | 1.150 | 655.0 | **8.80**** |
| C5 | | F3.5 | | 1.050 | 665.0 | 12.10 |
| C6 | | G7.5 | | 1.050 | 677.5 | **68.35**** |
| C7 | 1.100 | | 0.913 | 0.990 | 627.5 | 9.90 |
| C8 | | G3.5 | | 0.990 | 660.0 | **13.35**** |

**: out of the target

Mixture C2 was mixed with the same $V_w/V_p$ and Sp/P as C1 but different mixing time (F3.5). This concrete showed a larger slump flow and a longer V funnel time than mixture C1. This tendency corresponds with the result of series A in which a polycarboxylic ether based superplasticizer was used.

The mixtures C6-C8 were mixed by the gravity tilting mixer. Similar to the result of series A, the G-mixer mixing needed a higher $V_w/V_p$ than the F-mixer to obtain a proper viscosity of the fresh concrete, but the premium factor α, due to the mixing procedure, tends to be smaller than for the case of series A. This result implies that the naphthalene based superplasticizer used requires a smaller increase of $V_w/V_p$ to adjust the property of concrete according to less intensive mixing than the polycarboxylic ether based superplasticizer used.

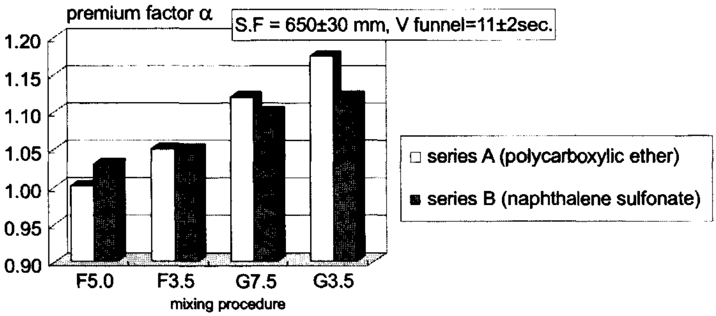


Figure 5.9 Influence of type of superplasticizer on premium factor α

Figure 5.9 shows the influence of the type of superplasticizer on the variation of the premium factor α due to the mixing intensity. The variation of α is clearly smaller for the naphthalene based superplasticizer used than for the polycarboxylic ether based superplasticizer used.

### 5.4.5 Results and discussions for tests on concrete: Series D

#### (1) General

Table 5.6 shows an overview of the results from the concrete test series D. The results of 4 mixtures, which were mixed by different mixing procedures and with fixed values of $V_w/V_p$=0.803 and Sp/P=0.50%, are shown.

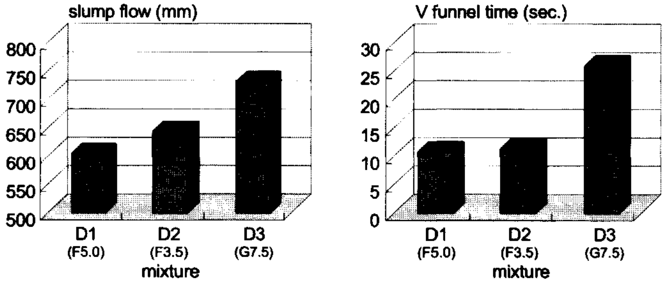
Table 5.6 Mixture parameter and results in Series D

| Mix No. | Mixing | A | $V_w/V_p$ | Sp/P (%) | SF/P (vol. %) | Slump flow (after mix) (mm) | V funnel time (sec) |
|---|---|---|---|---|---|---|---|
| D1 | F5.0 | 1.050 | 0.803 | 0.500 | 0 | 602.5** | 10.50 |
| D2 | F3.5 | | | | | 642.5 | 10.95 |
| D3 | G7.5 | | | | | 730.0** | 25.55** |
| D4 | G7.5 | | | | 3 | 625.0 | 12.70 |

**: out of the target

#### (2) Influence of mixing intensity for the same composition of mixtures

The mixtures D1, D2 and D3 had the same mixture composition and were mixed in different mixing ways, F5.0, F3.5 and G7.5. Figure 5.10 (a) and (b) shows the results of the slump flow test and V funnel test respectively in graphs.



(a) Slump flow

(b) V funnel

Figure 5.10 Results of slump flow and V funnel tests in Series D

From these results, it is clear that a more intensive mixing makes a concrete less deformable and less viscous. The slump flow value, which is considered to represent the deformability of the concrete, is smaller in the order of D1(F5.0)<D2(F3.5)<D3(G7.5).

The V funnel time is related to both deformability (deforming capacity) and viscosity (internal deforming resistance) of the fresh concrete. When the deformability is constant (slump flow is the same), a longer V funnel time represents a larger viscosity of the mixture. When the deformability is smaller (slump flow is smaller), the V funnel time tends to be longer if the viscosity of the mixture is constant. From this point of view, it can be clearly evaluated that the viscosity of the mixtures is smaller in the order of D1(F5.0)<D2(F3.5)<<D3(G7.5). As discussed in the results of series A, the mixture D3 might have the highest self compactability among these three concretes. However, it is a definitely unworkable concrete.

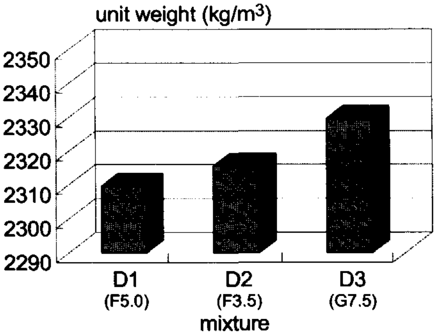


Figure 5.11 Variation of unit weight due to mixing procedure

Figure 5.11 shows the results for the unit weight of each mixture, by which the air content can be evaluated. A more viscous mixture had more weight in comparison. In other words, a mixture mixed by a more intensive mixing procedure contained more air.

**(3) Influence of silica fume on the properties of SCC**

In order to improve the workability of mixture D3, the effect of the application of silica fume (SF) was studied in mixture D4. In this mixture, a powder composition of "BSC:60% &FA2:37%&SF:3%(in volume)" was applied with constant values of $V_w/V_p$=0.803 and Sp/P=0.50% like in the mixtures D1-3. This mixture was mixed by mixing procedure G7.5 just like D3. From the test result, it was found that a 3% replacement of fly ash by silica fume can extremely enhance the workability of concrete. The mixture D4 including silica fume showed a smaller slump flow value and shorter V funnel time than D3, and they were comparable with the result for mixture D2 which had proper workability and self-compactability. This result suggests that the use of silica fume is helpful to produce SCC by a gravity mixer without increasing the amount of water compared to the SCC which can be produced by a forced mixer.

### 5.4.6 Hypothesis to explain the observed phenomena

#### (1) General

From the experimental results described previously, the following tendencies for the influence of the mixing efficiency on the properties of fresh concrete can be established in general.

(a) More intensive mixing makes the concrete less viscous when the water to powder volume ratio is constant.

(b) More intensive mixing requires a larger amount of superplasticizer in order to obtain the same deformability of the fresh concrete when the water to powder volume ratio is constant.

In order to explain these phenomena, the following three effects of the mixing procedure and intensity on the behavior of the concrete in the paste phase are suggested. The influence of the mixing effect is considered as a complex of these constitutive effects, and the degree of effectiveness seems to depend on the mixing method applied and the materials used.

#### (2) Effect on the dispersion of powder particles (Mixing Effect 1)

Intensive mixing disperses the powder particles better than less intensive mixing. In the case of poor mixing, small (or large) agglomerations of powder particles still remain in the paste phase of the concrete even if a superplasticizer is used. This agglomeration makes the paste phase of the concrete more viscous (higher deforming resistance) than well dispersed particles when $V_w/V_p$ is constant. Figure 5.12 shows this condition schematically.

#### (3) Effect on processing powder particles' surfaces (Mixing Effect 2)

When cement (binder) particles are mixed with water and superplasticizer, the initial hydration product is generated on their surface and polymers of superplasticizer adsorb on it. Intensive mixing probably breaks and tears off the initial hydration product from the surface of the cement (binder) particles and the process described above repeats again and again during the mixing. Figure 5.13 shows this condition schematically.

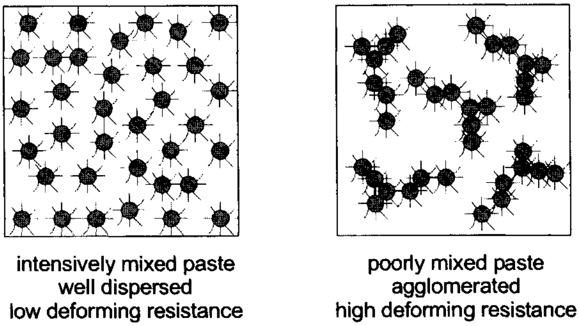


Figure 5.12 Schematic image of mixing effect on powder dispersion

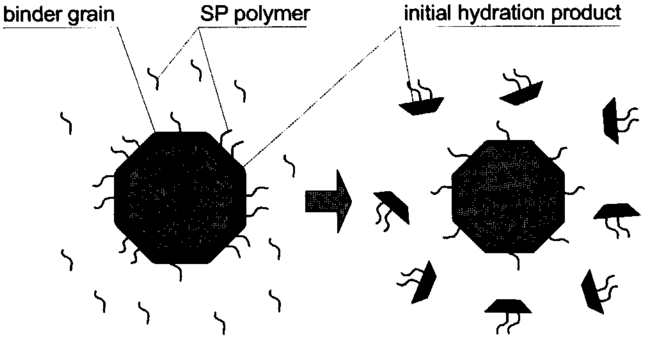


Figure 5.13 Schematic image of mixing effect on surface modification

In consequence, intensive mixing requires more superplasticizer than less intensive mixing to obtain the same slump flow value (deforming capacity), because it consumes a larger amount of superplasticizer during mixing. This consideration agrees well with the result of Sugamata's measurement shown in Figure 2.44 and 2.45. Furthermore, the fine pieces of hydration product possibly act as a lubricant among the binder particles and they make the concrete mixture less viscous (lower deforming resistance).

**(4) Effect on air bubble generation in the paste phase of fresh concrete (Mixing Effect 3)**
A more intensively mixed concrete mixture contains, at least as observed in this investigation, a larger amount of air. The entrained air bubbles might be very small and act as a good lubricant

among the aggregate and powder particles. As such, they could help to make the concrete mixture less viscous.

**(5) Role of silica fume in the paste phase of fresh concrete**

The particles of the silica fume are much smaller than the cement particles. The SF particles adsorbing SP polymers probably lubricate the movement of the cement particles. This effect can be considered as very similar to "Mixing Effect 2" mentioned above. As an evidence, replacing the fly ash by silica fume (mixture D3→D4) resulted in a smaller slump flow and a smaller viscosity. This is the same tendency as occurring between mixture D2 and D3 where the mixing intensity was drastically changed.

## 5.5 CONCLUSIONS

In this chapter, the influence of mixer type and mixing time on the fresh properties of SCC was experimentally studied in detail, also considering the type of chemical admixtures applied. From the results, the following conclusions can be drawn.

(1) SCC is producible not only by a forced mixer but also by a gravity tilting mixer.

(2) The most adequate values of water to powder volume ratio and dosage of superplasticizer depend on the mixing intensity. This means that a proper mixture proportion for SCC must be designed considering the intensity of the applied mixer.

(3) Self compactabity of fresh concrete can be realized if the concrete has a high deformability and a high segregation resistance even though the concrete is not workable.

(4) A concrete including welan gum requires a larger increase of $V_w/V_p$ than a non-welan gum concrete to adjust the workability of the fresh concrete due to a smaller intensity of mixing.

(5) The naphthalene sulfonate based superplasticizer used requires a smaller increase of $V_w/V_p$ than the polycarboxylic ether based superplasticizer used to adjust the workability of the fresh concrete due to the smaller intensity of mixing.

(6) A small dosage of silica fume can make fresh concrete significantly less viscous. This material is useful when producing SCC by a gravity mixer without increasing the water content.

(7) The influence of the mixing efficiency on the properties of fresh SCC can be explained by the effect of dispersion of powder particles, the effect of processing the powder particles' surfaces and the effect of air bubble generation.

# CHAPTER 6
# INFLUENCE OF MIXING EFFICIENCY AND CHEMICAL ADMIXTURES ON THE PROPERTIES OF FLOWABLE CEMENT PASTE

## 6.1 INTRODUCTION

In Chapter 5, it was clarified that the SCC mixture proportion, especially the adequate value of the water to powder volume ratio and the dosage of superplasticizer, was influenced by the mixing intensity even though constant properties of materials were used. Moreover, it was observed experimentally that the influence varied with the type of chemical admixtures applied. This result clarified that a proper mixture composition of SCC should be designed considering the intensity of mixing and the type of chemical admixture applied.

In this chapter, it is tried to understand the influence of the mixing efficiency and the chemical admixtures on the properties of SCC more specifically than in chapter 5. For this purpose it is supposed that the influence mentioned above acts predominantly on the properties of the paste phase of SCC which consists of water, powder materials and chemical admixtures. Therefore in the following sections, the fluctuation of the properties of cement paste with low water to cement ratio, as a result of the influence of mixing efficiency and the type of chemical admixtures, is investigated.

## 6.2 CHARACTERISTICS OF THE APPLIED MATERIALS

### 6.2.1 Cement

Table 6.1 shows the characteristics of the applied cement. BSC is a Dutch common blast furnace slag cement. All the cement used in this series of tests was produced in the same lot and delivered packed together in a large bag. Moreover, the cement was homogenized by a mechanical cement homogenizer before use to minimize the material properties fluctuation.

Table 6.1 Characteristics of the cement

| Material name | Brand | Density ($g/cm^3$) | Blaine ($m^2/kg$) | Clinker (%) | Slag (%) | Fly ash (%) | CaO (%) | $SiO_2$ (%) |
|---|---|---|---|---|---|---|---|---|
| Blast furnace slag cement (BSC) | CEMIJ CEM III/B 42,5 LH HS | 2.94 | 398 | 20.5 | 74.1 | 1.2 | 43 | 28 |

### 6.2.2 Chemical admixtures and water

Table 6.2 shows the characteristics of the superplasticizer used. SP-A and B are the superplasticizers of polycarboxylic ether complex (non-AE type). SP-C is a naphthalene sulfonate based one (AE type). SP-B has a similar active polymer as SP-A but the initial dispersibility is lower than A. However, SP-B has a better flowability retention. In order to obtain sufficient stability of the mixture during the test, SP-A and B are used together in a combining ratio of 1:1 in weight. SP-A and B are products of the Dutch market. SP-C is one of the most popular naphthalene sulfonate based superplasticizers in Japan.

Table 6.2 Characteristics of superplasticizer

| | Product name | Chemical description | AE type | Specific gravity* | Solid Concentration (%) |
|---|---|---|---|---|---|
| SP-A | Glenium 51 | Polycarboxylic ether complex | Non-AE | 1.10 | 35 |
| SP-B | Glenium 27 | Polycarboxylic ether complex | Non-AE | 1.05 | 20 |
| SP-C | Rheobuild SP-9HS | Naphthalene sulfonate base | AE | 1.20 | 30 |

*solution base

Besides the materials mentioned above, welan gum was used as a viscosity modifying admixture. When the welan gum was employed in this study, its dosage was always constant, being 0.05 weight % of unit water. As mixing water, de-ionized water was applied for all the mixtures tested in this series of tests.

## 6.3 EXPERIMENTAL PROGRAM

### 6.3.1 Variables

In order to clarify the influence of mixing efficiency and chemical admixtures on the properties of fresh cement paste specifically, the following conditions were fixed and varied in this series of test.

### (1) Fixed conditions

a) Powder composition

In this program, the powder composition was fixed at BSC 100%. No other mineral admixtures (powder materials) were applied.

b) Water

De-ionized water was used for all mixtures.

c) Temperature

The temperature of the mixtures after mixing was controlled at 20±1 °C strictly by controlling the temperature of the mixing water and the laboratory.

d) Mixer

All mixtures tested were mixed by the same mixer, a Hobart N-50. This mixer has three mixing speeds changeable by gear position. Each mixing speed corresponds to the following rotation and revolution rate.

Table 6.3 Performance of the mixer

| Gear position | Rotation rate (rpm) | Revolution rate (rpm) |
|---|---|---|
| Low speed | 139 | 61 |
| Middle speed | 285 | 125 |
| High speed | 591 | 259 |

In this investigation, Low and Middle speed positions were applied to mix the cement pastes.

e) Mixing volume

The volume of all mixtures tested was kept constant at 1.5 liters, to exclude the influence of the mixing volume from the evaluation of the mixing efficiency.

### (2) Varied conditions

**a) Mixing procedure**

For the evaluation of the mixing efficiency on the properties of fresh cement paste, the seven mixing procedures shown in Table 6.4 were prescribed and applied. All the materials necessary for a mixture, cement, water and chemical admixtures, were weighed in the mixer pot before the start of the mixing.

The order of the mixing intensity of the seven mixing procedures is as follows. *MX4* is considered as the standard mixing in this program.

Mixing intensity: *MX1* < *MX2* < *MX3* < *MX4* < *MX5* < *MX6* < *MX7*

Table 6.4 Mixing procedures (unit: sec.)

| Mixing Name | 1st mixing | Int. | 2nd mixing | Int. | 3rd mixing | | Int. | 4th mixing |
|---|---|---|---|---|---|---|---|---|
| | Low | | Low | | Low | Middle | | Low |
| *MX1* | 30 | (1) | 30 | (2) | 30 | - | (3) | 15 |
| *MX2* | | | 60 | | 60 | | | |
| *MX3* | | | | | - | 30 | | |
| *MX4* | | | | | | 60 | | |
| *MX5* | | | | | | 90 | | |
| *MX6* | | | | | | 120 | | |
| *MX7* | | | | | | 180 | | |

Interval (1) & (2) : scratching the mixer pot

Interval (3) : 5 min. rest & scratching the mixer pot

**b) Types and combinations of chemical admixtures**

In order to evaluate the influence of the type and the combination of chemical admixtures on the mixing efficiency, the following four combinations of chemical admixtures were applied.

*SP1* : Polycarboxylic ether superplasticizer (SP-A+SP-B=1:1) , non-AE type
*SP1W* : *SP1* and welan gum
*SP2* : Naphthalene sulfonate superplasticizer (SP-C), AE type
*SP2W* : *SP2* and welan gum

### 6.3.2 Test methods and measurement

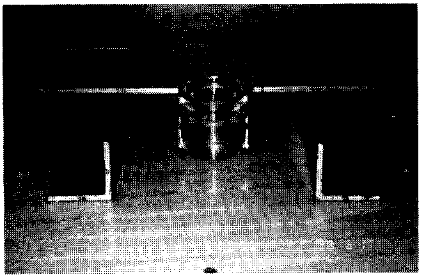
#### (1) Electric power consumption

During the mixing of the cement paste, the electric power consumption was measured in order to evaluate the mixing energy imparted to the mixture. Picture 6.1 shows the mixer and the electric power measuring device used in this experiment. The electric power was measured by a multi meter and recorded by a laptop computer during the mixing.

Picture 6.1 Mixer and electric power measuring device

**(2) Mini-slump test**

To evaluate the deformability (potentiality of deformation) of a cement paste mixture, the "Mini-slump test" [61] was used. Picture 6.2 shows the equipment for the Mini-slump test. It consists of a Mini-slump cone made of Plexiglas, a base plate made of Plexiglas board and a pair of guides to measure the flow diameter. Figure 6.1 shows the dimension of the Mini-slump cone.



Picture 6.2 Equipment for Mini-slump test

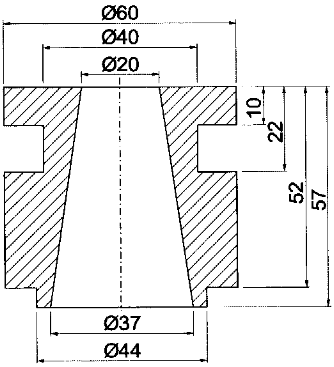
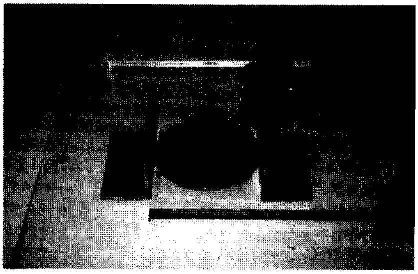


Figure 6.1 Dimension of Mini-slump cone

The test procedure involved the measurement of the spread diameter of a certain volume of cement paste placed in the cone which is positioned in the center of a horizontal base plate. After pouring the cement paste into the cone without causing it to overflow, the top of the sample is leveled by a straight edge to remove the excessive paste into a ditch around the top of the cone. The cone was then removed slowly upwards and away from the sample. The spread diameter of a given mixture represents the mean of two diameters, a maximum diameter and another perpendicular diameter, recorded at the end of the flow. Picture 6.3 shows an example of the measurement.



Picture 6.3 Example of mini-slump flow

### (3) Modified Marsh cone test

The modified Marsh cone test employed in this research measures the flow time of a given volume of cement paste through a funnel cone of a standard size. The Marsh cone used in this study has a capacity of 1,200 ml and an internal orifice diameter of 10 mm. Figure 5.2 shows the dimension of the cone. The time needed for a cement paste sample to flow through the funnel cone is basically dependent on both the viscosity (internal resistance to deformation) and the deformability (potentiality of deformation) of the mixture. When the deformability is comparable among some different mixtures, the flow time is proportional to the viscosity of the cement paste. In this study, the Marsh cone flow time is expected to represent the viscosity of the pastes tested.

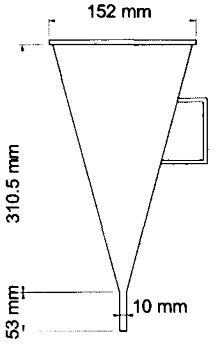


Figure 6.2 Dimension of Marsh cone

The funnel cone should be thoroughly cleaned and moisture of the interior should be wiped before use. The cone is placed vertically on a support frame and a graduated cylinder is placed under the funnel. A representative sample of cement paste is poured through a fine sieve, which can retain any clumps of cement, attached on the top of the cone plugging the lower orifice of the cone by a finger. The volume of the sample poured is controlled to be a constant volume of 750 ml, because the flow speed of a paste through the cone is influenced by the head pressure. Then the mixture is allowed to flow out of the funnel to the graduated cylinder and the time is measured from when the flow volume reaches 100 ml till it reaches 400 ml. This is because the cumulative flow time could deviate from linearity as the flow approaches the end [61]. Picture 6.4 shows the equipment for the Marsh cone test.

Picture 6.4 Equipment for Marsh cone flow test

### (4) Viscometer measurement

In order to determine the rheological characteristics of the cement pastes, the relative yield value and the relative viscosity, a viscometer described in 2.3.10 (2) was employed in this study. Figure 6.3 shows the rotation speed profile applied for the viscometer. The solid line indicates the planned rotation schedule for a measurement. It increases stepwise with 5 by 5 rpm every 7-8 seconds and a measuring duration continues for 75 seconds. The points plotted in the graph indicate an example of practical record which shows the actual variation of the rotation speed. For all the measurements by the viscometer, this profile was applied in this study.

The viscometer measurement was executed three times sequentially using one sample for each mixture.

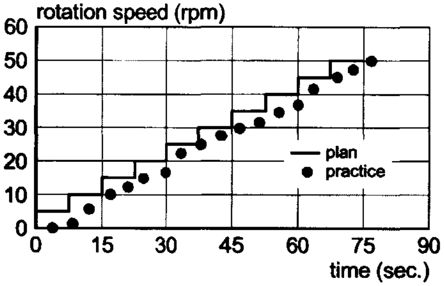


Figure 6.3 Rotation speed profile for viscometer test

### (5) Unit weight (air content) and sedimentation (bleeding) test

The unit weight of the cement pastes mixed was measured to know the air content in the mixture. 100ml of cement paste was weighed using a glass-made graduated cylinder. The air content of the mixture weighed can be calculated considering the mixture proportion which provides a unit weight of the mixture including no air.

After the weight measurement, the cement paste in the graduated cylinder was left without movement for 1 hour avoiding moisture loss. During the leaving time, sedimentation of cement particles might occur and clear bleeding water might come up to the top of the mixture. The volume of the bleeding water was measured by the graduation of the cylinder.

### 6.3.3 Test program A : applying a polycarboxylic ether based superplasticizer

**(1) Common conditions for test program A**

(a) Type of admixtures

The following type of chemical admixture was applied for all the mixtures tested.

- *SP1*: Polycarboxylic ether superplasticizer (SP-A+SP-B=1:1), non-AE type

(b) Executed tests and measurements

The following tests and measurements were executed for all the mixtures tested.

- Electric power consumption during the mixing
- Mini-slump test
- Modified marsh cone test
- Viscometer measurement
- Unit weight and sedimentation test

**(2) Test series A1**

In this series, it was tried to find the most adequate water to powder volume ratio ($V_w/V_p$) and dosage of superplasticizer (Sp/P) which realize the target Mini-slump value and the target Marsh cone flow time defined below in order to investigate the influence of the mixing intensity on the proportioning of cement pastes which consist of the same materials and have physically constant properties evidenced by the result of the Mini-slump test and the modified Marsh cone test.

The testing conditions are as follows:

(a) Applied mixing procedures:

*MX1, MX2, MX3, MX4, MX5, MX6, MX7*

(b) Target properties for Mini-slump test and modified Marsh cone test:

Target Mini-slump value = 110 ± 2 mm

Target Marsh cone flow time = 45 ± 3 sec.

**(3) Test series A2**

In this series, it was tried to find the most adequate dosage of superplasticizer (Sp/P) which realizes the target Mini-slump value when fixing the $V_w/V_p$ that is the target value for mixing procedure *MX4* obtained in the test series A1 in order to investigate the influence of mixing intensity on viscosity of cement pastes which consist of the same materials and are specified by a constant value of water to powder volume ratio ($V_w/V_p$).

The testing conditions were as follows:

(a) Applied mixing procedures:

MX1, MX2, MX3, MX4, MX5, MX6, MX7

(b) Fixed value of $V_w/V_p$ :

The target value for *MX4* in the test series A1

(c) Target properties for Mini-slump test:

Target Mini-slump value = 110 ± 2 mm

**(4) Test series A3**

In this series, seven different dosages of superplasticizer were adopted to investigate their influence on the behavior of the cement pastes independent of the influence of the mixing procedure. The mixing procedure and the value of the water to powder volume ratio ($V_w/V_p$) were fixed.

The testing conditions were as follows:

(a) Applied mixing procedure:

*MX4*

(b) Fixed value of $V_w/V_p$ :

The target value for *MX4* in the test series A1

(c) Dosage of superplasticizer:

Varied around the target value for *MX4* in the test series A1

### 6.3.4 Test program B : applying naphthalene sulfonate based superplasticizer

**(1) Common conditions for test program B**

(a) Type of admixtures:

The following type of chemical admixture was applied for all the mixtures tested.

- *SP2*: Naphthalene sulfonate superplasticizer (SP-C), AE type

(b) Executed tests and measurements:

The following tests and measurements were executed for all the mixtures tested:

- Electric power consumption during the mixing
- Mini-slump test
- Modified marsh cone test
- Viscometer measurement

- Unit weight and sedimentation test

**(2) Test series B1**

In this series, the following factors were adopted for the same purpose as for the series A1:

(a) Applied mixing procedures:

*MX1, MX2, MX4, MX6, MX7*

(b) Target properties for mini-slump test and modified Marsh cone test:

Target mini-slump value = 110 ± 2 mm

Target Marsh cone flow time = 45 ± 3 sec.

**(3) Test series B2**

In this series, the following factors were adopted for the same purpose as for the series A2:

(a) Applied mixing procedures:

*MX1, MX2, MX4, MX6, MX7*

(b) Fixed value of $V_w/V_p$ :

The target value for *MX4* in the test series B1

(c) Target properties for Mini-slump test:

Target Mini-slump value = 110 ± 2 mm

**(4) Test series B3**

In this series, the following factors were adopted for the same purpose as for the series A3: Three different dosages of superplasticizer were applied.

(a) Applied mixing procedure:

*MX4*

(d) Fixed value of $V_w/V_p$ :

The target value for *MX4* in the test series B1

(e) Dosage of superplasticizer:

Varied around the target value for *MX4* in the test series B1

### 6.3.5 Test program C : applying a viscosity modifying admixture : welan gum

**(1) Common conditions for test program C**

(a) Type of admixtures:

The welan gum was applied for all the mixtures tested.

The dosage of the welan gum was constant at 0.05 weight % of water.

(b) Executed tests and measurements:

The following tests and measurements were executed for all the mixtures tested:

- Electric power consumption during the mixing
- Mini-slump test
- Modified marsh cone test
- Viscometer measurement
- Unit weight and sedimentation test

**(2) Test series C1**

In this series, the following factors were adopted for the same purpose as for the series A:

(a) Type of admixtures:

*SP1W*: Polycarboxylic ether superplasticizer (SP-A+SP-B=1:1), non-AE type, and welan gum

(b) Applied mixing procedures:

*MX1, MX2, MX4, MX6, MX7*

(c) Target properties for Mini-slump test and modified Marsh cone test:

Target mini-slump value = 110 ± 2 mm

Taget Marsh cone flow time = 45 ± 3 sec.

**(3) Test series C2**

In this series, the following factors were adopted for the same purpose as for the series A2:

(a) Type of admixtures:

*SP1W*: Polycarboxylic ether superplasticizer (SP-A+SP-B=1:1), non-AE type, and welan gum

(b) Mixing procedure:

*MX1, MX2, MX3, MX4, MX5, MX6, MX7*

(c) Fixed value of $V_w/V_p$ :

The target value for *MX4* in the test series C1

(d) Target properties for mini-slump test:

Target mini-slump value = 110 ± 2 mm

**(4) Test series C3**

In this series, the following factors were adopted for the same purpose as for the series B1:

(a) Type of admixtures:

*SP2W*: Naphthalene :sulfonate superplasticizer (SP-C), AE type, and welan gum

(b) Mixing procedure:

*MX2, MX4, MX6:*

(c) Target properties for mini-slump test and modified Marsh cone test:

Target Mini-slump value = 110 ± 2 mm

Target Marsh cone flow time = 45 ± 3 sec.

**(5) Test series C4**

In this series, the following factors were adopted for the same purpose as for the series B2:

(a) Type of admixtures:

*SP2W*: Naphthalene sulfonate superplasticizer (SP-C), AE type, and welan gum

(b) Mixing procedure:

*MX2, MX4, MX6,*

(c) Fixed value of $V_w/V_p$ :

The target value for *MX4* in the test series C3

(d) Target properties for Mini-slump test:

Target Mini-slump value = 110 ± 2 mm

## 6.4 ANALYSIS OF THE RESULTS OF THE ELECTRIC POWER MEASUREMENT AND THE VISCOMETER TEST

### 6.4.1 Analyses with regard to the power consumption

Figure 6.4 shows an example record of the electric power measured during the mixing of the cement paste (sample data for *MX4* in the test series A1). The periods with no electric power correspond to the time for scratching and resting in the mixing procedure *MX4*. The "Power A" means the total electric power necessary to run the mixer for mixing of a cement paste. The "Power B" means the electric power subtracting the power necessary for running the mixer with an empty pot from the "Power A".

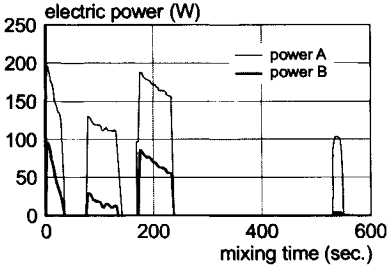


Figure 6.4 Example of electric power measurement

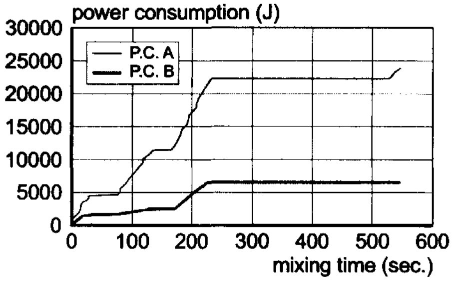


Figure 6.5 Example of electric power consumption

Figure 6.5 shows an example of the cumulative electric power curve (electric power consumption curve) calculated from the record shown in Figure 6.4. The final value of the cumulative curve is the total consumption of electric power during mixing. The "Power Consumption A (P.C.A)" is the cumulative power consumption based on the "Power A". In the same manner, the "Power Consumption B (P.C.B) " is the cumulative power consumption based on the "Power B" and it is possible to be considered as the pure amount of energy consumed by the cement paste.

For all cement paste mixtures tested in this study, P.C.A and P.C.B were calculated. Basically, P.C.B was used to evaluate the test results. In some cases P.C.A was also considered to understand the results.

### 6.4.2 Analysis of the viscometer test results

Figure 6.6 shows an example record of a viscometer measurement expressing the relation between the shear resistance value T [N·mm] and the rotational speed of the measuring vessel N [rpm]. The dots are recorded experimental data. The data corresponding to a rotation speed below 10 rpm are neglected because of the low accuracy of the measurement. The thick line is a regression line for all the data plotted in this graph, and the thin line is a regression line for the data measured between 10 rpm and 20 rpm of the rotation speed.

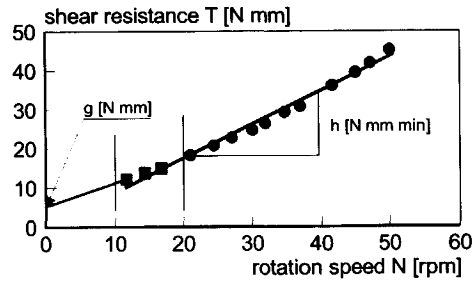


Figure 6.6 Example of viscometer measurement

The variables $g$ and $h$ were designated as relative yield value [N·mm] and relative viscosity [N·mm·min] respectively by the equation (2.5). Corresponding to the definition, the relative yield value and the relative viscosity of the sample data shown in Figure 6.6 should be evaluated as a function of the thick line. However, in some cases, the variable $g$ of the thick line function becomes a very small number, even a negative value, and it is physically meaningless as a yield value of a cement paste. In its physical meaning, the yield value is the shear resistance corresponding to the rotation speed N=0 rpm. Therefore, the relative yield value is evaluated by the thin line representing the regression line of experimental data measured between 10 rpm and 20 rpm of the rotation speed in order to avoid an underestimation of the yield characteristics of the mixture tested in this study. On the other hand, the relative viscosity of a mixture is evaluated as the inclination of the thick line representing the regression line of all the data obtained from a measurement.

In this study, the viscometer measurement was executed three times sequentially for each mixture of cement paste with an identical sample. A test result of both relative yield value and relative viscosity of each mixture is evaluated by an average value of three data obtained from the three measurements.

## 6.5 RESULTS AND DISCUSSIONS FOR TEST PROGRAM A : Applying Polycarboxylic Ether Based Superplasticizer

### 6.5.1 Results of test series A1

**(1) Target ratios $V_w/V_p$ and Sp/P for each mixing procedure**

In order to realize the target value of the mini-slump test (110±2mm) and the Marsh cone flow time (45±3sec.), it was tried to adjust the water to powder volume ratio ($V_w/V_p$) and the dosage of superplasticizer (Sp/P) for each different mixing procedure.

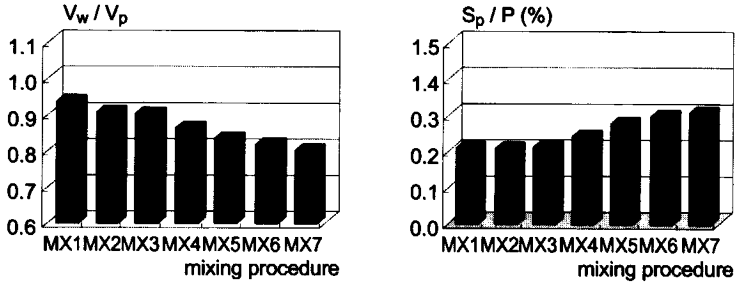


Figure 6.7 Variation of $V_w/V_p$ and Sp/P in test series A1

Figure 6.7 shows the variation of $V_w/V_p$ and Sp/P dependent on the mixing procedure. It was clear that different values of $V_w/V_p$ and Sp/P were required to realize a constant mini-slump flow and Marsh cone flow time when applying different mixing procedures even though the same materials were used. When a lower value of $V_w/V_p$ was required, a larger value of Sp/P was necessary. This is the same tendency as obtained for the concrete tests performed in Chapter 5.

Figure 6.8 (a) shows the relation between $V_w/V_p$ and the power consumption. $V_w/V_p$ shows a good linear relation with the logarithm of P.C.B. Figure 6.8 (b) shows the relation between Sp/P and the power consumption. Sp/P showed a good linear relation with the simple P.C.B. For mixing with larger energy, a lower value of $V_w/V_p$ and a larger dosage of superplasticizer were required.

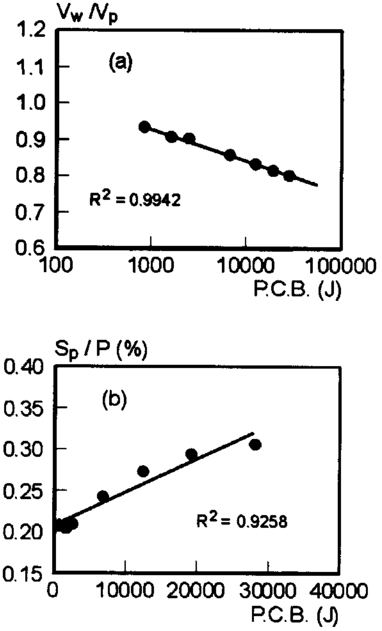


Figure 6.8 $V_w/V_p$ and Sp/P versus power consumption in test series A1

### (2) Air content and bleeding volume for each mixing procedure

Figure 6.9 (a) shows the relation between the air content and the electric power consumption. The air content correlated linearly well with the simple P.C.B.

On the basis of these results, it can be concluded that mixing with higher energy generates a larger volume of air bubbles in the cement paste mixture. The effect of the air bubbles, which is expected to lubricate the flow of the mixture, may result in a lower value of $V_w/V_p$ to realize the most adequate viscosity of a mixture. This phenomenon corresponds to the hypothesis of "Mixing Effect 3" established in Chapter 5.

Figure 6.9 (b) shows the relation between the bleeding water volume and the electric power consumption. The bleeding water volume showed a good linear relation with the logarithm of P.C.B.

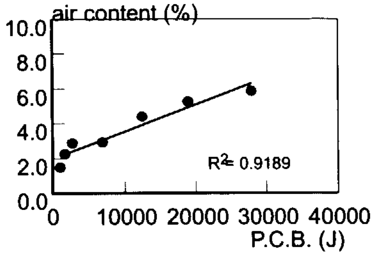


Figure 6.9 (a) Air content versus power consumption in test series A1

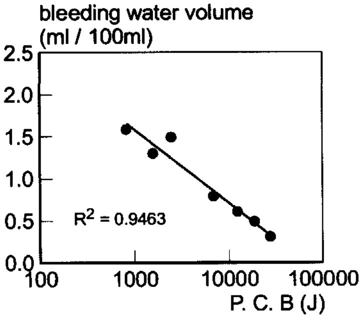


Figure 6.9 (b) Bleeding water volume versus power consumption in test series A1

The volume of the bleeding water tended to increase when the mixing energy was relatively small. This is because of the larger value of $V_w/V_p$ in case of smaller mixing energy to realize the target property of fresh cement paste. Figure 6.10 shows the relation between $V_w/V_p$ and the volume of bleeding water observed in this series. There is an excellent linear correlation. This phenomenon can be understood through the mechanism of the hypothesis of "Mixing Effect 1" established in Chapter 5.

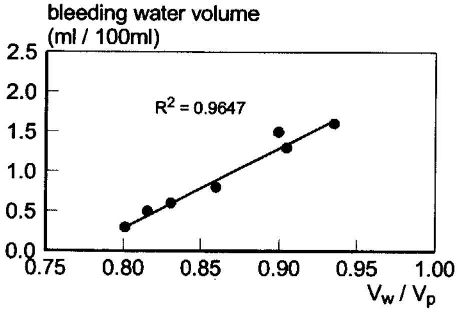


Figure 6.10 Bleeding water volume versus $V_w/V_p$ in test series A1

In the case of a poorly mixed cement paste (small mixing energy), agglomeration of cement particles still remains in the mixture even if a superplasticizer is used. This agglomeration makes the cement paste more viscous (higher deforming resistance) than well dispersed particles when $V_w/V_p$ is constant. Therefore, the value of $V_w/V_p$ must be larger to make the mixture adequately less viscous when the mixing energy is small. But then, the amount of "free water" becomes large, which lubricates the movement of the cement paste, but as well causes the increase of bleeding.

### (3) Relative viscosity and relative yield value for each mixing procedure

The relative viscosity (*h* [N·mm·min]) and the relative yield value (*g* [N·mm]) of each mixture were determined by the viscometer measurement. Figure 6.11 shows the variation of *h* and *g* dependent on the mixing procedure.

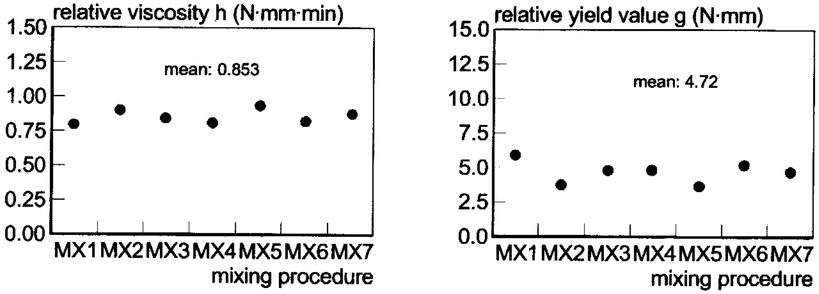


Figure 6.11 Variation of *h* and *g* in test series A1

For the relative viscosity *h*, the average value is 0.853 [N·mm·min] and the data are distributed in a small range around the average. The variation seems to be independent of the mixing procedure. The variation of the relative yield values *g* shows a similar tendency as the variation of *h*. The average value is 4.72 [N·mm] and the data are distributed around the average in a small range. This is logical because the same deformability and the viscosity are targed for all the mixtures in this series.

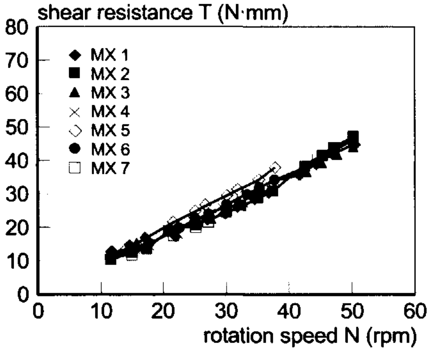


Figure 6.12 T versus N in Test Series A1

Figure 6.12 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second measurement for each mixture. The seven different mixtures prepared according to the seven different mixing procedures show almost the same behavior in the viscometer as a consequence of controlling the mini-slump flow and the Marsh cone flow time. In other words, they can be evaluated as the same characteristics of mixtures rheologically.

### 6.5.2 Results of test series A2

**(1) Target Sp/P for each mixing procedure under a fixed $V_w/V_p$ condition**

In this series, the water to powder volume ratio ($V_w/V_p$) was fixed at the value obtained for the test case *MX4* in series A1, and the mixing procedure was varied among *MX1 – 7*. In order to realize the target value of the mini-slump test (110 ± 2 mm), the dosage of superplasticizer (Sp/P) was adjusted for each different mixing procedure applying the chemical admixture type *SP1*.

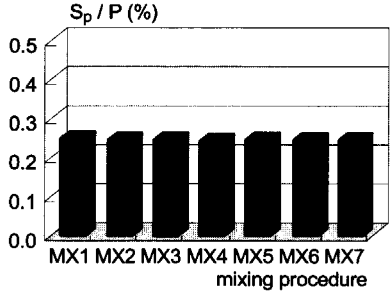


Figure 6.13 Variation of Sp/P in test series A2

In these tests, as shown in Figure 6.13, the variation of Sp/P depending on the mixing procedures resulted in an almost constant value in order to realize the target mini-slump flow for each different mixing intensity. This result does not correspond to the result obtained in Chapter 5. In the tests on concrete series D of Chapter 5, a fixed mixture composition resulted in a smaller value of the slump flow when the mixing was more intensive, and a larger value of the slump flow was obtained when poorer mixing was applied. This result led to the hypothesis of "Mixing Effect 2" that specifies a larger consumption of superplasticizer by the surface modification of powder particles caused by intensive mixing. However, this effect could not be observed in the results of the paste tests performed in this study. The reason of this matter will be discussed in a later section.

### (2) Marsh cone flow time

In this series, $V_w/V_p$ was fixed at the ratio that realizes the target Marsh cone flow time (45±3sec.) when applying the mixing procedure *MX4*. The variation of the Marsh cone flow time for each mixing procedure applied is shown in Figure 6.14 (a). The values fluctuated due to the mixing procedures in spite of the control of the Mini-slump flow values.

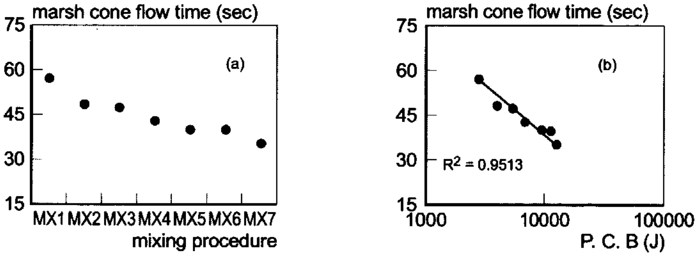


Figure 6.14 Variation of Marsh cone flow time in test series A2

Figure 6.14 (b) shows the relation between Marsh cone flow time and power consumption. P.C.B shows a good correlation with the result of the Marsh cone flow time.

A more intensive mixing shortens the Marsh cone flow time compared to a poorer mixing. This means that a more intensive mixing makes a cement paste mixture less viscous. This phenomenon agrees well with the hypothesis of "Mixing Effect 1" and "Mixing Effect 3" established in Chapter 5.

### (3) Air content and bleeding volume for each mixing procedure

Figure 6.15 shows the relation between the air content and the electric power consumption. The variation of the air content correlates linearly well with the variation of P.C.B. More intensive mixing generates a larger amount of air in the mixtures, and this result confirms "Mixing Effect 3" established in Chapter 5.

On the other hand, the variation of the volume of bleeding water does not indicate a clear tendency with regard to the variation of the power consumption. Most of data resulted in a volume of around 1.0 ml (/100ml) due to the constant $V_w/V_p$.

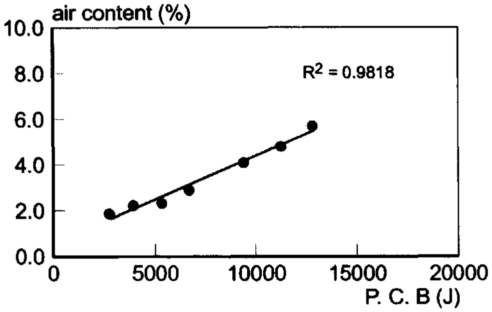


Figure 6.15 Air Content versus Power Consumption in Test Series A2

### (4) Relative viscosity and relative yield value for each mixing procedure

Figure 6.16 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second viscometer measurement for each mixture in series A2. It is observed that the inclinations of the lines change in dependence of the mixing procedure.

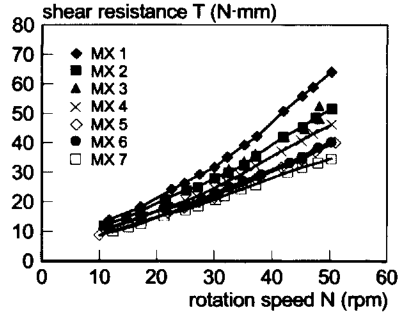


Figure 6.16 T versus N in Test Series A2

Figure 6.17 shows the variation of the relative viscosity (*h* [N·mm·min]) and the relative yield value (*g* [N·mm]) dependent on the power consumption. The values of *h* varied remarkably and the maximum value (for *MX1*) was even twice as large as the minimum value (for *MX7*) in spite of the fact that the mixture composition was constant. This is apparently caused by the difference in mixing intensity. Mixing with larger energy makes a mixture less viscous. The same conclusion was obtained by the measurement of the Marsh cone flow time. The hypothesis of "Mixing Effect 1" and "Mixing Effect 3" established in Chapter 5 were confirmed by this result again.

On the other hand, the values *g* were found to be in a very small range and they were almost constant. On the basis of this result, it can be strongly emphasized that the relative yield value evaluated in this study correlates very well with the mini-slump flow value independently from the Marsh cone flow time. Furthermore, the average value of 4.76 [N·mm] is very close to the average value found in series A1 (4.72 [N·mm]).

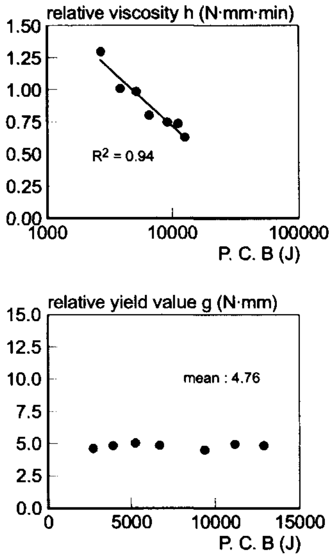


Figure 6.17 Variation of *h* and *g* in test series A2

Figure 6.18 shows the relation between *h* and the Marsh cone flow time. An excellent linear relationship is found. From this result, it can be concluded that the measurement of the Marsh cone flow time employed in this study is a very suitable testing method for evaluating the viscosity of cement pastes under the condition of a controlled mini-slump flow value.

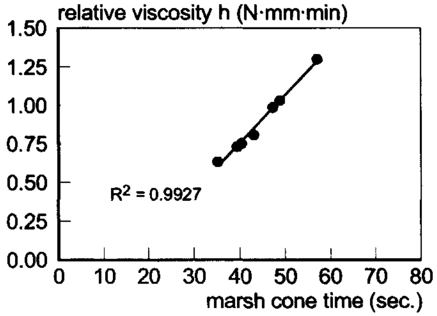


Figure 6.18 *h* versus marsh cone flow time in test series A2

### 6.5.3 Results of test series A3

#### (1) Variation of mini-slump flow value and Marsh cone flow time dependent on Sp/P

In this series, the water to powder volume ratio ($V_w/V_p$) was fixed at the value for the test case *MX4* in series A1, and a fixed mixing procedure *MX4* was applied. The type of chemical admixture was also fixed (*SP1*) but its dosage (Sp/P) was varied in seven different amounts in order to evaluate the pure influence of the dosage of superplasticizer on the behavior of cement paste.

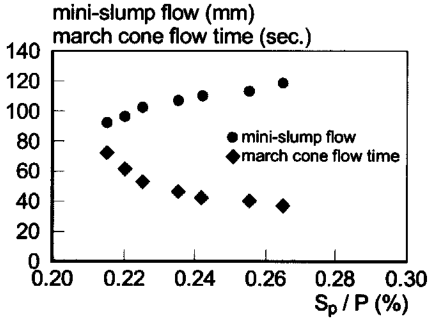


Figure 6.19 Variation of mini-slump flow and marsh cone flow time in test series A3

Figure 6.19 shows the variation of the mini-slump flow value and the Marsh cone flow time dependent on the dosage of *SP1*. The mini-slump flow values increased as Sp/P increased and they showed a good linear correlation. On the other hand, the variation of Marsh cone flow time showed a negative correlation with the ratio Sp/P. This result implies two possible kinds of background phenomena. Firstly, an increase of the dosage of *SP1* might reduce the viscosity of the cement paste. Secondly, the Marsh cone flow time might not depend only on the viscosity but also on the value of the mini-slump flow (deformability). This point will be discussed later considering the results of the other test series together.

#### (2) Variation of power consumption dependent on Sp/P

Figure 6.20 shows the variation of the power consumption dependent on the dosage of superplasticizer. An increase of Sp/P resulted in a reduction of the power consumption.

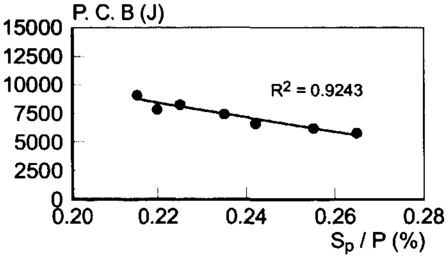


Figure 6.20 Power Consumption versus Sp/P in Test Series A3

### (3) Variation of air content and bleeding volume dependent on Sp/P

The values of air content varied around 3 % and were not influenced by the variation of Sp/P. The bleeding volume was also not clearly influenced by the dosage of superplasticizer, and a constant value of $V_w/V_p$ probably governs the amount of bleeding.

### (4) Relative viscosity and relative yield value dependent on Sp/P

Figure 6.21 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second viscometer measurement for each mixture in this series. The increase of Sp/P made the lines shift downward and the inclinations decrease.

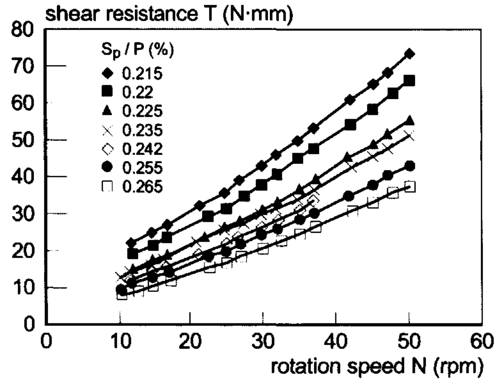


Figure 6.21 T versus N in Test Series A3

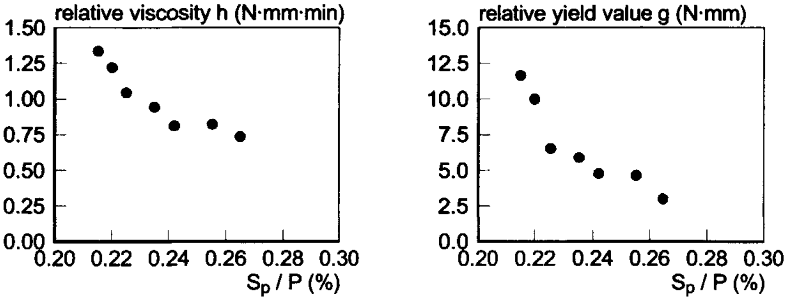


Figure 6.22 Variation of *h* and *g* in Test Series A3

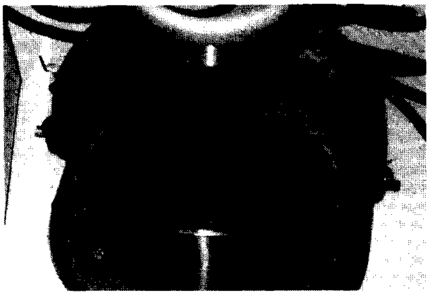
Figure 6.22 shows the variation of the relative yield value (*g* [N·mm]) and the relative viscosity (*h* [N·mm·min]) dependent on Sp/P. Both values of *g* and *h* were reduced as the dosage of superplasticizer increased. From this result, it is clear that the superplasticizer used in this series both decreased the yield value and reduced the viscosity of a cement paste mixture. And this effect of *SP1* is considered to result in the reduction of mixing power consumption mentioned above.

### 6.5.4 Evaluation for the hypotheses of the mixing effect under the application of *SP1*

According to the experimental results obtained above, the hypothesized "Mixing Effect 1 (Dispersion of powder particles)" and "Mixing Effect 3 (Air bubble generation)" can be considered to be applicable to the behavior of the cement pastes tested. However, the hypothesis of "Mixing Effect 2 (Processing of powder particles surface)" is not applicable to the results found in this test program. Here a reason for this observation is discussed.

Using the same cement (BSC100%) and the same superplasticizer (SP-A&B=1:1) the most adequate $V_w/V_p$ and Sp/P for SCC were found by the general purpose approach already in Chapter 4 (see Tables 4.5 and 4.7). In the mortar test, the most adequate $V_w/V_p$ was 0.815 and the most adequate Sp/P was 0.55%. In the concrete test, the most adequate Sp/P was 0.70% to obtain a slump flow of 650 mm. These values of Sp/P are much larger than the values applied in this program on cement paste (0.2-0.3 %).

When mixing a cement paste in which $V_w/V_p$ was 0.815 and Sp/P was 0.55%, adequate values for mortar according to the mixing procedure *MX4*, the mini-slump value was 154.5 mm, the Marsh cone flow time was 27.5 sec. and the mixture was completely segregated, in other words there was an "over-dosage" (see Picture 6.5). In order to explain this phenomenon, the hypothesis of "Mixing Effect 2" is applicable.



Picture 6.5 Segregated cement paste with adequate Sp/P for mortar

During the mixing of concrete or mortar, which includes aggregates in the mixtures, a much larger shear energy is supposed to be induced to the paste phase due to the action of solid grains of aggregates than during the mixing of a paste without aggregates. In this situation, the phenomenon hypothesized in the "Mixing Effect 2" must occur and a larger amount of superplasticizer is necessary to obtain adequate properties of the mortar or the concrete than for the paste mixed alone. In other words, the surface modification effect does not happen during the procedures of paste mixing employed in this study, but it is applicable for the mixing of mortar or concrete. From this evaluation, it can be concluded that the aggregate plays a very important role for the mixing of concrete especially with regard to the properties of the paste phase of the mixture, and it is not correctly simulated by the mixing test in the paste without aggregates as performed in this study.

## 6.6 RESULTS AND DISCUSSIONS OF TEST PROGRAM B : Applying a Naphthalene Sulfonate Based Superplasticizer

### 6.6.1 Results of test series B1

**(1) Target $V_w/V_p$ and Sp/P for each mixing procedure**

Different values of $V_w/V_p$ and Sp/P were required to realize a constant mini-slump flow and Marsh cone flow time, just like in the test series A1. Figure 6.23 shows the comparison between the test series A1 and B1 with regard to the variation of $V_w/V_p$ and Sp/P.

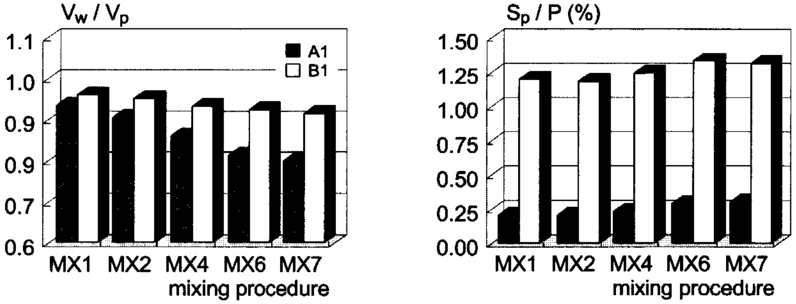


Figure 6.23 Variation of $V_w/V_p$ and Sp/P in test series A1 and B1

In series B1, a type of superplasticizer different from that used in test series A1 was applied. Therefore, the values of Sp/P are quite different and they are not comparable, but the tendency depending on the mixing procedure is similar. On the other hand, the variation of $V_w/V_p$ shows an interesting feature. In this series, both the maximum and the minimum values of $V_w/V_p$, dependent on the mixing procedure (0.960 for *MX1* and 0.915 for *MX7*), were larger than in series A1 (0.935 for *MX1* and 0.800 for *MX7*). This means that the naphthalene sulfonate based superplasticizer employed in this program required a larger value of $V_w/V_p$ than the polycarboxylic ether based superplasticizer used in the program A when the same mixing procedure was applied. Furthermore, it can be concluded that the difference between the maximum and the minimum values of $V_w/V_p$, dependent on the mixing procedure in series B1 (0.045), is significantly smaller than the difference in series A1 (0.135). In other words, the cement paste mixtures with *SP2* are less sensitive than the mixtures with *SP1* to the adjustment of $V_w/V_p$ against a change of the mixing intensity. This is the same tendency as observed in the concrete tests reported in Chapter 5.

Both $V_w/V_p$ and Sp/P showed good correlations with the power consumption (P.C.B) as well as for the series A1.

### (2) Air content and bleeding volume for each mixing procedure

Figure 6.23 shows the comparison between the test series A1 and B1 with regard to the variation of the air content.

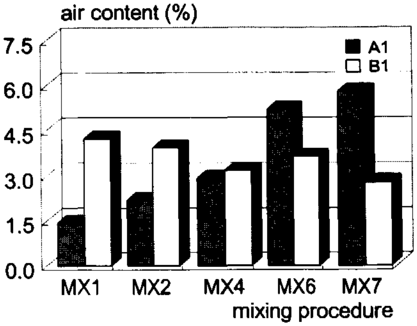


Figure 6.24 Variation of air content in test series A1 and B1

In series B1, the air content decreased accordingly with more intensive mixing. This is contrary to series A1 in that the air content increased as the mixing energy increased. This phenomenon can be explained by the difference in mixing effect for *SP1* and *SP2*. *SP1* is a non-AE type of polycarboxylic ether based superplasticizer. Therefore, the air content is small in the initial period of mixing and air bubbles are generated during the energetic mixing. On the other hand, *SP2* is an AE-type of naphthalene sulfonate based superplasticizer and it chemically generates entrained air bubbles in the initial period of mixing. Therefore, the air content is large enough for a short mixing time and longer mixing extinguishes the air bubbles in the mixture. In this case, electric energy is not consumed so much during the extra mixing and the mixture is only like stirred. Therefore, the hypothesis of "Mixing Effect 3" established in Chapter 5 is not applicable to a cement paste with *SP2*.

The bleeding volume did not change clearly dependent on the mixing procedures, because the change of $V_w/V_p$ was very small.

### (3) Relative viscosity and relative yield value for each mixing procedure

Figure 6.25 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second measurement for each mixture in this series. The five different mixtures mixed according to the five different mixing procedures show an almost similar behavior in the viscometer as observed in series A1. This is a consequence of controlling the mini-slump flow and the Marsh cone flow time.

Figure 6.26 shows the comparison between the series A1 and B1 with regard to the variation of relative viscosity (*h* [N·mm·min]) and relative yield value (*g* [N·mm]) dependent on the mixing procedure.

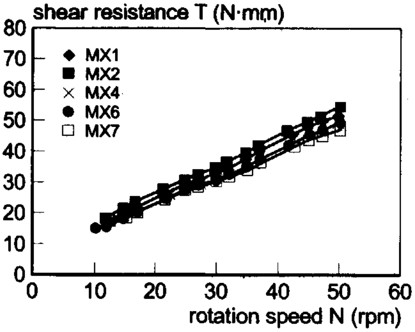


Figure 6.25 T versus N in Test Series B1

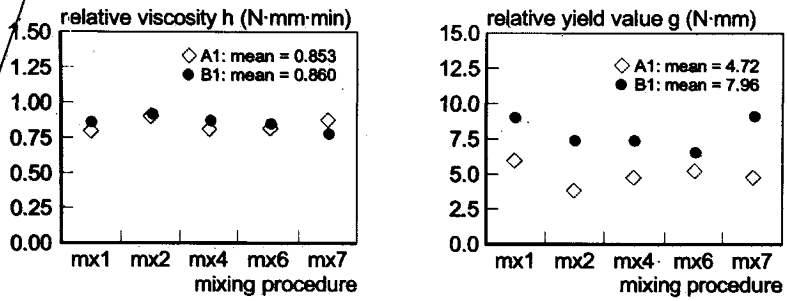


Figure 6.26 Variation of *h* and *g* in test series A1 and B1

The average values of *h* for both series A1 and B1 are quite close. On the other hand, the average value of *g* for B1 is larger than for A1 although the mini-slump flow value was controlled at the same target value.

### 6.6.2 Results of test series B2

**(1) Target value Sp/P for each mixing procedure under a fixed $V_w/V_p$ condition**

In this series, the water to powder volume ratio ($V_w/V_p$) was fixed at the value obtained for the test case *MX4* in the test series B1, and the mixing procedure was varied. In order to realize the target value of the mini-slump test (110 ± 2 mm), the dosage of superplasticizer (Sp/P) was adjusted.

A variation of the necessary ratio Sp/P dependent on the mixing procedure was not found and a constant value (1.24 %) was required. This result proves that the hypothesis of "Mixing Effect 2" that supposes a consumption of superplasticizer by processing of powder particles' surface is not applicable for the cement pastes mixed by the procedure employed in this study applying *SP2* as well.

### (2) Marsh cone flow time

Figure 6.27 (a) shows the comparison between the series A2 and B2 with regard to the variation of the Marsh cone flow time depending on the mixing procedure. They showed almost the same result. As shown in Figure 6.27 (b), the logarithm of P.C.B has a good linear correlation with the Marsh cone flow time in series B2 as well as in series A2, though the consumed electric power in B2 was smaller than in A2.

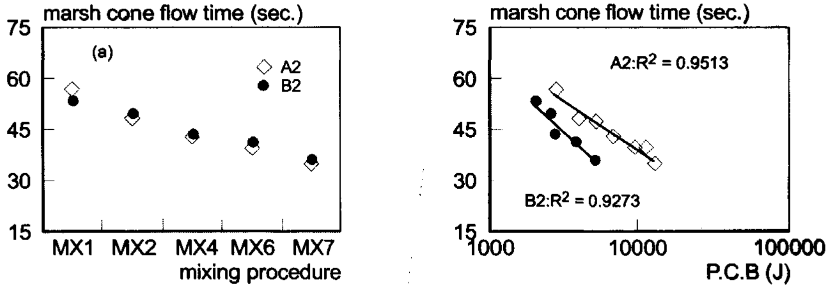


Figure 6.27 Variation of Marsh cone flow time in test series A2 and B2

### (3) Air content and bleeding volume for each mixing procedure

Figure 6.28 shows the comparison between the test series A2 and B2 with regard to the variation of the air content. They show a contrary tendency, the reason of which has been explained in 6.6.1 (2).

The bleeding volumes did not vary so much depending on the mixing intensity due to the constant value of $V_w/V_p$.

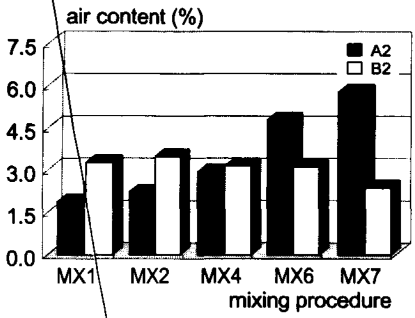


Figure 6.28 Variation of air content in test series A2 and B2

### (4) Relative viscosity and relative yield value for each mixing procedure

Figure 6.29 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second viscometer measurement for each mixture in series B2. The distribution of lines is similar to Figure 6.16 for series A2.

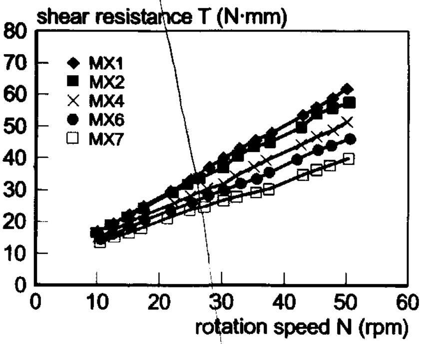


Figure 6.29 T versus N in test series B2

Figure 6.30 shows the comparison between the test series A2 and B2 with regard to the variation of the relative viscosity (*h* [N·mm·min]) and relative yield value (*g* [N·mm]). The variations of *h* dependent on the mixing procedure in both series A2 and B2 are almost the same. Mixing with larger energy makes a mixture less viscous. The same conclusion was obtained by the measurement of the Marsh cone flow time (see Figure 6.27). It implies that the hypothesis of "Mixing Effect 1" established in Chapter 5 is applicable for the cement pastes with naphthalene sulfonate based superplasticizer, too. The variation of *h* correlated well with the P.C.B., and also with the Marsh cone flow time.

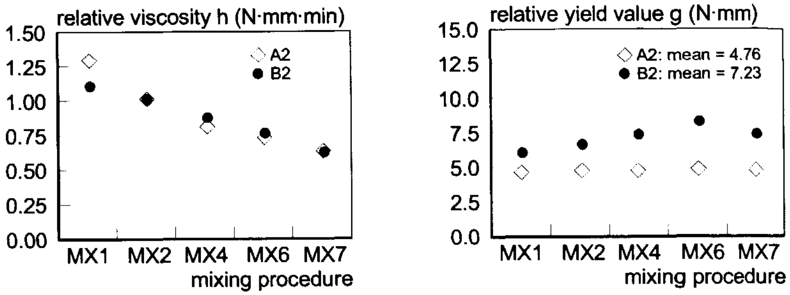


Figure 6.30 Variation of *h* and *g* in test series A2 and B2

On the other hand, the values of *g* were in a relatively small range because of the controlled mini-slump flow value. However, the average value of *g* for B2 is larger than for A2, but very close to the average value for series B1 where the same type of superplasticizer was applied.

### 6.6.3 Results of test series B3

**(1) Variation of mini-slump flow value and Marsh cone flow time dependent on Sp/P**

In this series, the water to powder volume ratio ($V_w/V_p$) was fixed at the value for the test case *MX4* in series B1, and a fixed mixing procedure *MX4* was applied. The type of chemical admixture was also fixed (*SP2*) but its dosage (Sp/P) was varied.

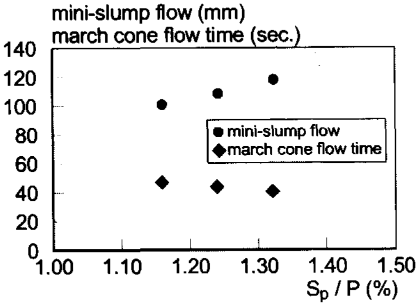


Figure 6.31 Variation of mini-slump flow and Marsh cone flow time in test series B3

Figure 6.31 shows the variation of the mini-slump flow value and the Marsh cone flow time dependent on the dosage of *SP2*. The Mini-slump flow values were increased as Sp/P increased and they showed a linear correlation just like in series A3. On the other hand, the variation of the Marsh cone flow time showed a negative correlation with the Sp/P as well as observed in series A3, but the degree of variation was very small.

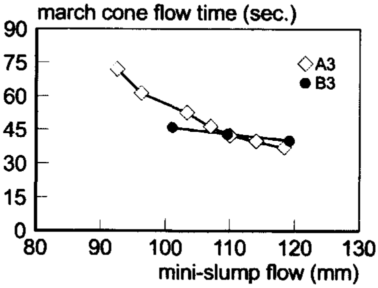


Figure 6.32 Marsh cone flow time versus mini-slump flow in test series A3 and B3

Figure 6.32 shows the variation of the Marsh cone flow time dependent on the mini-slump flow values for both the series A3 and B3. From this graph, it can be found that the dosing of *SP2* decreases the Marsh cone flow time to a smaller extent than the dosing of *SP1*.

### (2) Variation of power consumption dependent on Sp/P

P.C.B showed only a small variation, almost independent of Sp/P. This tendency is different from the result obtained in series A3 for *SP1*.

### (3) Variation of air content and bleeding volume dependent on Sp/P

The air content varied around 3 % and was not influenced by the variation of Sp/P. The bleeding volume was also not clearly influenced by the dosage of superplasticizer, and a constant value of $V_w/V_p$ probably governed the amount of bleeding.

### (4) Relative viscosity and relative yield value dependent on Sp/P

Figure 6.33 shows the variation of the relative yield value (*g* [N·mm]) and the relative viscosity (*h* [N·mm·min]) dependent on Sp/P. The value of *g* was reduced as the dosage of superplasticizer was increased just like in series A3. However, the value of *h* was almost constant independently of the variation of Sp/P. This phenomenon differs from the result obtained in A3 (see Figure 6.22).

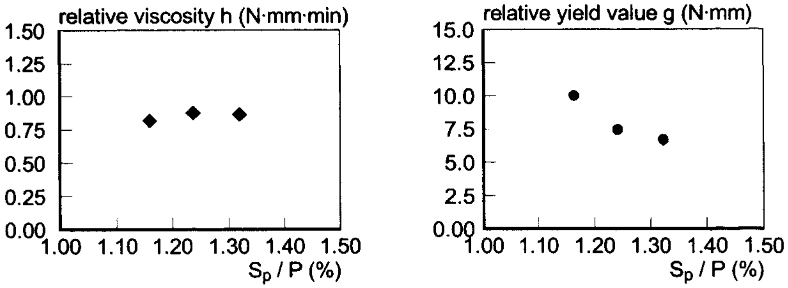


Figure 6.33 Variation of *h* and *g* in test series B3

Figure 6.34 shows the comparison between the test series A3 and B3 with regard to the variation of the relative viscosity (*h* [N·mm·min]) dependent on the mini-slump flow value. In case of applying *SP2*, the values of *h* were not varied as much as for *SP1* and they are almost constant. From this result, it was clear that dosing *SP2*, a naphthalene sulfonate based superplasticizer, did not reduce the viscosity of the cement paste mixtures, and it was a different characteristic from *SP1*, a polycarboxylic ether based superplasticizer.

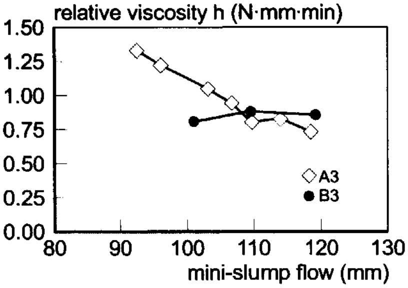


Figure 6.34 *h* versus mini-slump flow in test series A3 and B3

Herewith, the question about the Marsh cone flow time noted in 5.5.3 (1), whether it is dependent only on the viscosity of the mixture or also on the deformability, is solved. According to the results of this series, the Marsh cone flow time was reduced as Sp/P increased in spite of the fact that the value of *h* was not reduced. This result verified that the Marsh cone flow time does not depend only on the viscosity of the mixture but also on the deformability (yield value).

### 6.6.4 Estimation of the difference between the dispersion mechanism for *SP1* and *SP2* based on the mixing power consumption

Comparing the results of the test programs A and B applying *SP1* and *SP2* respectively, it was observed that the values of the electric power consumption measured during the mixing in the program B are remarkably smaller than the values in the program A.

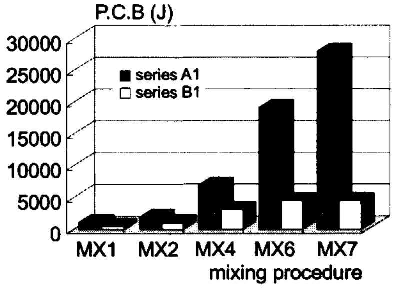


Figure 6.35 Variation of electric power consumption in test series A1 and B1

Figure 6.35 shows the difference of mixing energy (P.C.B) consumed in the series A1 and B1 dependent on the mixing procedures. For all the mixing procedures, the values of consumed energy (P.C.B) are smaller in series B1 than in series A1, and the difference becomes larger as the mixing is more intensive.

In the case of the series A1, the energy consumption increases remarkably as the mixing procedure becomes more intensive. On the other hand, the energy consumption in series B1 does not change so remarkably as in series A1 depending on the mixing procedure. From this result, a difference in "dispersion mechanism" between *SP1* and *SP2* can be presumed and understood as shown by the following consideration.

The dispersion mechanism of the superplasticizer is mainly classified into two effects. One is the "electrostatic repulsion effect" and the other is the "steric hindrance effect". The detailed explanations of both dispersion effects are described in 2.4.1 (1). An actual superplasticizer is considered to cause dispersibility combining both effects, and the degree of influence is dependent on the molecule structure of the superplasticizer.

The dispersion effect of the polycarboxylic ether based superplasticizer is mainly qualified as "steric hindrance effect" in general. It has a low electrostatic repulsion effect as well, but the steric hindrance effect is dominant. On the other hand, a naphthalene sulfonate based superplasticizer acts to disperse cement particles mainly by the electrostatic repulsion effect.

The above mentioned difference of dispersion mechanism between the polycarboxylic ether based superplasticizer (*SP1*) and the naphthalene sulfonate based superplasticizer (*SP2*) is used in trying to understand the energy consumption during the mixing.

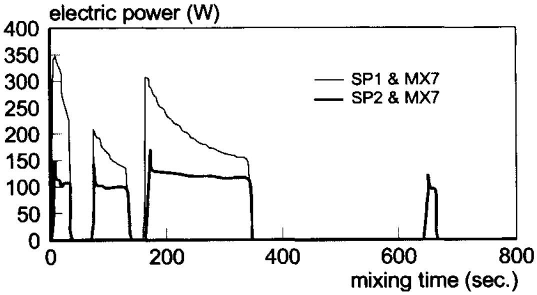


Figure 6.36 Variation of electric power for *SP1* and *SP2*

Figure 6.36 shows the records of the electric power during the mixings for the cases *SP1 & MX7* (series A1) and *SP2 & MX7* (series B1). The value of the electric power includes the power necessary for running the mixer itself (96-97 [W] for low speed mixing and 98-101 [W] for middle speed mixing). The periods of 0 [W] are the rest periods.

In the case of the mixture applying *SP1*, a large electric power was required to start mixing and the power decreased gradually during the mixing. This result implies that the initial state of the mixture is very rough and viscous, and the load on the mixer is high. However, the load decreases with the progress of mixing, which means that the mixture becomes smooth and less viscous due to the dispersion condition of the cement particles improved by the mixing effect. In other words, the superplasticizer used cannot disperse the cement particles spontaneously and the effect of mixing takes the principal role in dispersing the cement particles. In this state, the superplasticizer is mainly expected to keep the distance between the particles by the steric hindrance effect wedging its molecule body into the space between the particles separated by the mixing action.

On the other hand, in the case of the mixture applying *SP2*, a so large electric power was not required to start the mixing and very small excess power was consumed to run the mixer. This result implies that the mixture became smooth very quickly after starting the mixing. In other words, the superplasticizer used can disperse the cement particles spontaneously by the electrostatic repulsion effect in the very initial state of mixing, and a little electric energy was consumed during the mixing that might contribute to disperse the cement particles (Mixing Effect 1) but the degree was considerably smaller than for a mixture with *SP1*.

However, it is also the fact that this small contribution of the mixing for the dispersion of the cement particles results in a large effect to decrease the viscosity of the mixture in the case of the application of *SP2*. This can be understood from the Figures 6.27 and 6.30. The same mixing procedures resulted in almost the same Marsh cone flow time and relative viscosity although the mixtures with *SP2* consumed much less mixing energy than the mixtures with *SP1*.

### 6.6.5 Evaluation of the hypotheses for the mixing effect under the application of *SP2*

According to the experimental results obtained above, the hypothesized "Mixing Effect 1 (Dispersion of powder particles)" is applicable to the behavior of the cement pastes applying *SP2* as well as for *SP1*. However, the degree of the effect for the mixtures with *SP2* is smaller than for the mixtures with *SP1* because of the different "dispersion mechanisms" of the superplasticizers. However, the small mixing effect in a mixture with *SP2* results in a comparable change of the viscosity to a mixture with *SP1*.

The hypothesized "Mixing Effect 2 (Processing powder particles' surface)" was not applicable to the behavior of the cement pastes tested in this program for the same reason as explained in 6.5.4.

The hypothesis of "Mixing Effect 3 (Air bubble generation)" was not adequate to apply to the cement pastes with *SP2*, because it was an AE-type of superplasticizer which generated entrained air bubbles chemically in the initial period of mixing.

## 6.7 RESULTS AND DISCUSSION OF TEST PROGRAM C : Applying Welan Gum

### 6.7.1 Results of test series C1 (chemical admixture type: *SP1W*)

#### (1) Target $V_w/V_p$ and Sp/P for each mixing procedure

Different values of $V_w/V_p$ and Sp/P were required to realize a constant mini-slump flow and

Marsh cone flow time in agreement with the result of series A1. Figure 6.37 shows the comparison between the test series A1 and C1 with regard to the variation of $V_w/V_p$ and Sp/P

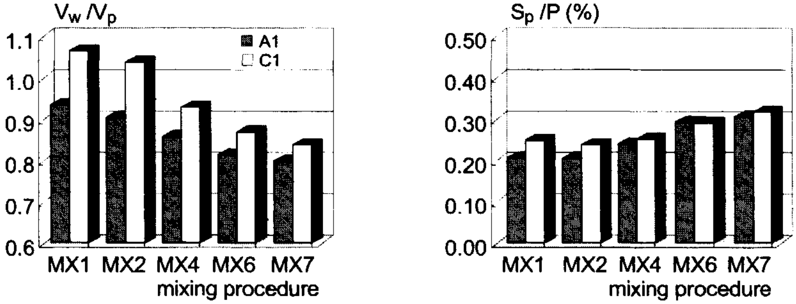


Figure 6.37 Variation of $V_w/V_p$ and Sp/P in test series A1 and C1

The values of $V_w/V_p$ in the series C1 are larger than in the series A1 for each mixing procedure. This means that the dosing of welan gum raises the value of $V_w/V_p$ to realize the target property of the cement paste. Furthermore, the range of variation for C1 is larger than for A1. This means that a mixture with welan gum is more sensitive on balancing the value of $V_w/V_p$ to adjust the fresh property at the target depending on the mixing intensity. These results correspond very well to the results for the concrete tests described in Chapter 5.

On the other hand, the values of Sp/P for C1 are larger than for A1, especially when the mixing intensity is small. This means that a mixture with welan gum requires a larger dosage of superplasticizer to realize the target property of the cement paste than a non-welan gum mixture, especially when the mixing intensity is not sufficient. Furthermore, the variation range of Sp/P for C1 is smaller than for A1. This means that the addition of welan gum makes a cement paste mixture less sensitive than a non-welan gum mixture on adjusting the dosage of superplasticizer depending on the mixing intensity.

Both $V_w/V_p$ and Sp/P showed good correlations with the power consumption (P.C.B) just as for the series A1.

**(2) Air content and bleeding volume for each mixing procedure**

The air content showed a good positive linear relation with the simple P.C.B and the bleeding volume correlates linearly well with the logarithm of P.C.B as well as for the series A1. Therefore, it can be concluded that the hypothesis of "Mixing Effect 1"and "Mixing Effect 3" are applicable for the mixtures including welan gum as well as for the mixtures without welan gum on the basis of the explanation described in 6.5.1 (2).

### (3) Relative viscosity and relative yield value for each mixing procedure

Figure 6.38 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second measurement for each mixture in this series. The five different mixtures mixed according to the five different mixing procedures show almost the same behavior in the viscometer.

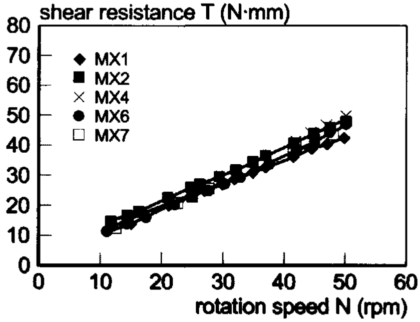


Figure 6.38 T versus N in Test Series C1

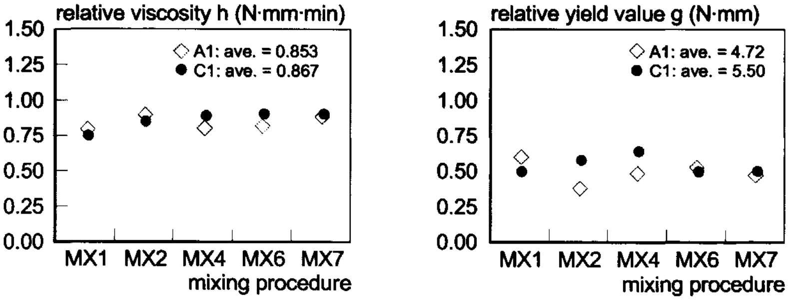


Figure 6.39 Variation of *h* and *g* in test series A1 and C1

Figure 6.39 shows the variation of relative viscosity (*h* [N·mm·min]) and relative yield value (*g* [N·mm]) dependent on the mixing procedure. The variations of both *h* and *g* were in a small range just like for series A1 because of the controlled mini-slump flow and Marsh cone time.

### 6.7.2 Results of test series C2 (chemical admixture type: *SP1W*)

**(1) Target Sp/P for each mixing procedure under a fixed $V_w/V_p$ condition**

In this series, the water to powder volume ratio ($V_w/V_p$) was fixed at the value obtained for the test case *MX4* in series C1, and the mixing procedure was varied. In order to realize the target value of the mini-slump test (110±2mm), the dosage of superplasticizer (Sp/P) was adjusted. Figure 6.40 shows the comparison between the series A2 and C2 with regard to the variation of the Sp/P.

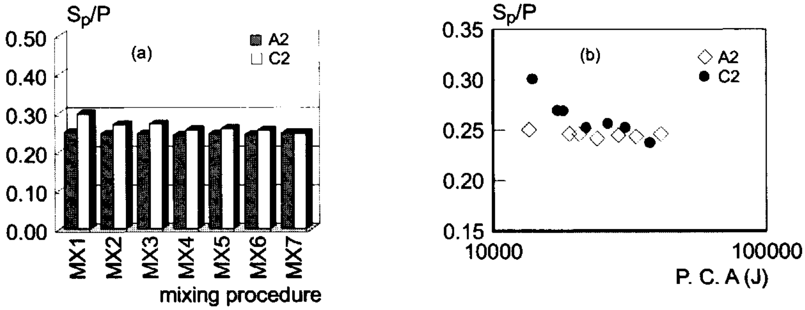


Figure 6.40 Variation of Sp/P in test series A2 and C2

In series C2, the variation of Sp/P dependent on the mixing procedures was in a small range, but the degree of the variation is apparently larger than for series A1. Figure 6.40 (b) shows the relation between the required Sp/P and the power consumption (P.C.A). An obvious tendency for C2 is that a larger energy of the mixing procedure requires a smaller dosage of superplasticizer. This result is contrary to the result obtained in Chapter 5. In the tests on concrete reported in Chapter 5, a more intensive mixing required a larger dosage of superplasticizer to realize a constant slump flow of both the fresh concrete with and without welan gum. This result led to the hypothesis of "Mixing Effect 2" that expects consumption of superplasticizer by processing the powder particles surface caused by intensive mixing. However, in this series of tests on cement paste, this effect could not be observed, and even a contrary tendency was obtained. From this result, it turns out that the hypothesis of "Mixing Effect 2" does not hold for the tests on cement paste under the mixing method employed in this study. Then, why did the values of Sp/P tend to decrease as the mixing energy was increased in this series? This phenomenon seems to relate to the hypothesis of "Mixing Effect 1". According to this hypothesis, intensive mixing disperses cement particles well and it contributes to the reduction of the viscosity of the cement paste. This effect can be expected to contribute to the increase of the deformability as well, and it may result in a reduction of the dosage of superplasticizer. In series A2, this effect could not be observed, but it became obvious in series C2. This seems to be an influence of adding welan gum.

### (2) Marsh cone flow time

Figure 6.41 shows the comparison between the series A2 and C2 with regard to the variation of the Marsh cone flow time depending on the mixing procedure.

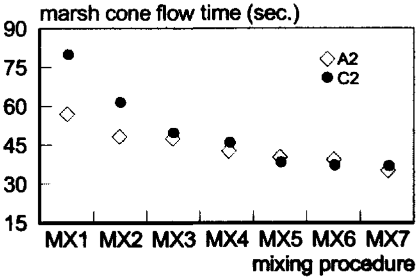


Figure 6.41 Marsh cone flow time versus mixing procedures in test series A2 and C2

From this comparison, it is found that the range of variation of the Marsh cone flow time for C2 is larger than for A2, especially when the mixing intensity is small. This result proved that the dosing of welan gum makes a cement paste mixture more sensitive to the variation of viscosity depending on the mixing intensity. This conclusion corresponds well with the argument raised for the comparison between the series A1 and C1 described in 6.7.1(1).

### (3) Air content and bleeding volume for each mixing procedure

Figure 6.42 shows the comparison between the test series A2 and C2 with regard to the variation of the air content. The air content in C2 was smaller than in A2 for each mixing procedure, and the reduction was larger when the mixing was more intensive. This result implies that the dosing of welan gum reduced the degree of the "Mixing Effect 3" comparing to the non-welan gum mixtures.

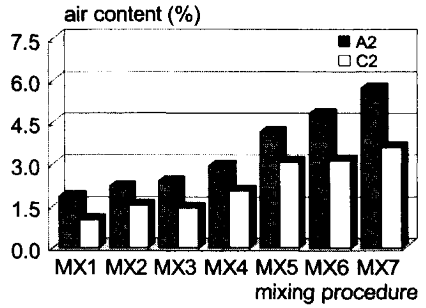


Figure 6.42 Air content versus mixing procedures in test series A2 and C2

The bleeding volumes did not vary so much depending on the mixing intensity. Most of the data resulted in around 1.0-1.5 ml due to the constant $V_w/V_p$.

**(4) Relative viscosity and relative yield value for each mixing procedure**

Figure 6.43 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second viscometer measurement for each mixture in series C2. The distribution of lines is similar to the one presented in Figure 6.16 for the series A2.

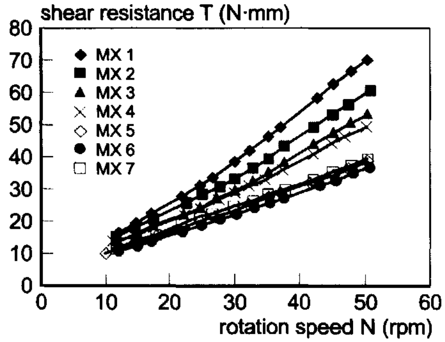


Figure 6.43 T versus N in Test Series C2

Figure 6.44 shows the comparison between the test series A2 and C2 with regard to the variations of the relative viscosity (*h* [N·mm·min]) and the relative yield value (*g* [N·mm]). In this comparison, it is found that the variation range of *h* for C2 is slightly larger than for A2, especially when the mixing intensity is small. This result proves that the dosing of welan gum makes a cement paste mixture more sensitive to the variation of viscosity depending on the mixing intensity as discussed in 6.7.1 (1).

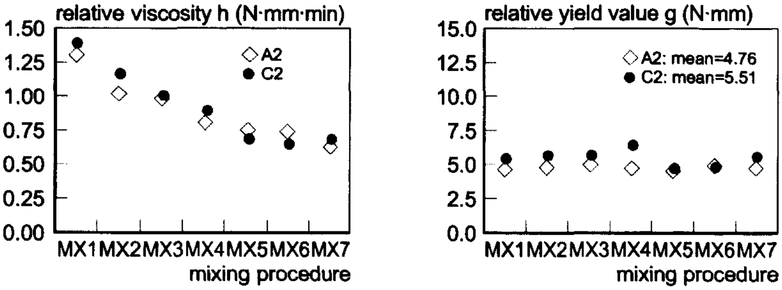


Figure 6.44 Variation of *h* and *g* in test series A2 and C2

On the other hand, the values of *g* were in a very small range. The average value of *g* is 5.51 [N·mm] in this series and it is very close to the average value in the series A1, A2 and C1 where the same type of the superplasticizer was applied.

### 6.7.3 Results of test series C3 (chemical admixture type: *SP2W*)

#### (1) Target $V_w/V_p$ and Sp/P for each mixing procedure

Different values of $V_w/V_p$ and Sp/P were required to realize a constant mini-slump flow and Marsh cone flow time in agreement with the result in the series B1. Figure 6.45 shows the comparison between the test series B1 and C3 with regard to the variation of the mini-slump flow and the Marsh cone flow time.

The values of $V_w/V_p$ in the series C3 are larger than in the series B1 for each mixing procedure. This means that the dosing of welan gum raises the value of $V_w/V_p$ necessary to realize the target property of the cement paste. This is the same phenomenon as occurred in the series A1 and C1 employing a polycarboxylic ether based superplasticizer (see Figure 6.37).

However, the variation range according to the mixing intensity for C3 is comparable to the result for A1. This means that the dosing of welan gum does not influence the sensitivity on balancing the value of $V_w/V_p$ to adjust the fresh property at the target depending on the mixing intensity. This is a different tendency from the result observed in the series A1 and C1, and this phenomenon seems to relate to the different characteristics of the two superplasticizers employed and the combination with the effect of welan gum.

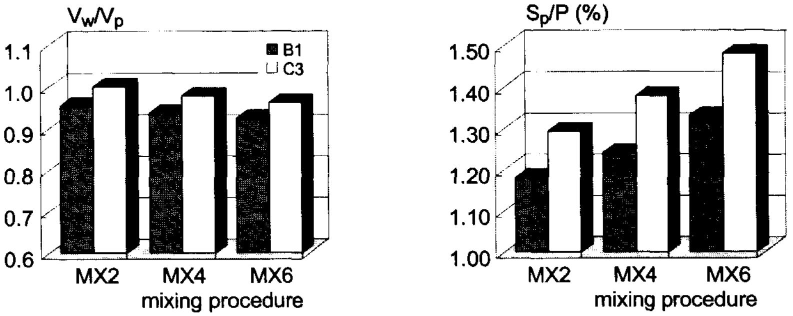


Figure 6.45 Variation of $V_w/V_p$ and Sp/P in test series B1 and C3

On the other hand, the comparison of Sp/P between the test series B1 and C3 leads to the following points of consideration. The values of Sp/P for C3 are larger than for B1. This means that a mixture with welan gum requires a larger dosage of superplasticizer to realize the target property of cement paste than a non-welan gum mixture. This tendency is clearer than for the relation between C1 and A1 employing *SP1* (see Figure 6.37). The variation range according to the mixing intensity for C3 is comparable with the result for B1. This means that the dosing of welan gum does not influence the sensitivity on balancing the value of Sp/P to adjust the fresh property at the target depending on the mixing intensity. This tendency is also different from the results observed in the series A1 and C1.

### (2) Air content and bleeding volume for each mixing procedure

The air content decreased accordingly as the mixing energy increased. This is the same tendency as found in series B1 and a result contrary to what was observed in the series A1 and C1. This difference is apparently due to the different characteristics of superplasticizers as explained in 6.6.1(2).

The range of variation of the air content for C3 was larger than for B1. This means that the dosing of welan gum makes the cement paste mixtures tend to loose the air content due to mixing under the combination with *SP2*.

The bleeding volume did not change clearly according to the mixing energy, because the change of $V_w/V_p$ was very small.

### (3) Relative viscosity and relative yield value for each mixing procedure

Figure 6.46 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second measurement for each mixture in this series. The three different mixtures prepared according to the three different mixing procedures show almost the same behavior in the viscometer.

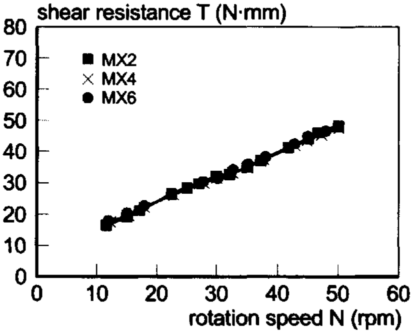


Figure 6.46 T versus N in test series C3

Figure 6.47 shows the variation of relative viscosity (*h* [N·mm·min]) and relative yield value (*g* [N·mm]) dependent on the mixing procedure. The variations of both *h* and *g* were in a small range as well as for series A1, B1 and C1 because of the controlled mini-slump flow and Marsh cone time

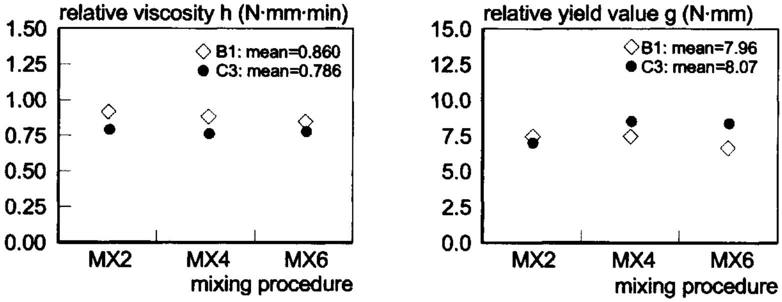


Figure 6.47 Variation of *h* and *g* in test series B1 and C3

The average value of *h* is close to the average obtained in series A1, B1 and C1. On the other hand, the average value of *g* is larger than found in the series A1 and C1 (applying *SP1*) but quite close to the average of the series B1 (applying *SP2*).

### 6.7.4 Results of test series C4 (chemical admixture type: *SP2W*)

**(1) Target Sp/P for each mixing procedure under a fixed $V_w/V_p$ condition**

In this series, the water to powder volume ratio ($V_w/V_p$) was fixed at the value obtained for the test case *MX4* in series C3, and the mixing procedure was varied. In order to realize the target value of the mini-slump test (110±2mm), the dosage of superplasticizer (Sp/P) was adjusted.

The variation of Sp/P dependent on the mixing procedures resulted in a constant value to realize the target mini-slump flow as well as in the series B2, and the dosing of welan gum showed no clear influence on the variation of Sp/P. This is a different tendency from the influence of welan gum shown in the comparison between the results of series A2 and C2 described in 6.7.2 (1). In the result of series C2 applying *SP1W*, a larger energy of mixing required a smaller amount of superplasticizer to keep a constant mini-slump flow value. On the other hand, a constant value of Sp/P was required in series C4 applying *SP2W*. This phenomenon is considered to relate to different degrees of "Mixing Effect 1" for the pastes with *SP1* and *SP2*. Therefore, the influence of welan gum on the mixing effect is different depending on the type of superplasticizer used.

**(2) Marsh cone flow time**

Figure 6.48 shows the comparison between the series B2 and C4 with regard to the variation of Marsh cone flow time depending on the mixing procedure.

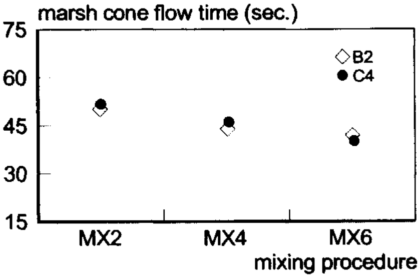


Figure 6.48 Marsh cone flow time versus mixing procedures in test series B2 and C4

From this comparison, it is found that the variation range of the Marsh cone flow time for C4 is almost as same as for B2. This result proves that the dosing of welan gum has no clear influence on the sensitivity of the variation of viscosity depending on the mixing intensity when combined with *SP2*. This is a different tendency from the result shown in a comparison between the series A2 and C2 employing *SP1*.

### (3) Air content and bleeding volume for each mixing procedure

The amount of air in the mixtures reduced as the mixing energy increased. This is the same tendency with the results of series B2 (applying *SP2*) and a contrary tendency to the results of series A2 and C2 (applying *SP1*). The variation of the air content in C4 was comparable to the results obtained in B2 (see Figure 6.28). It implies that the dosing of welan gum does not clearly influence the variation of air content dependent on the mixing intensity when combined with *SP2*. This is a different tendency from the influence of the welan gum when combined with *SP1* as discussed in 6.7.2 (3). The bleeding volumes did not vary so much due to the constant ratio $V_w/V_p$.

### (4) Relative viscosity and relative yield value for each mixing procedure

Figure 6.49 shows the relation between the rotation speed N [rpm] and the shear resistance T [N·mm] obtained by the second viscometer measurement for each mixture in series C4. The distribution of lines is the same as shown in Figure 6.29 for series B2.

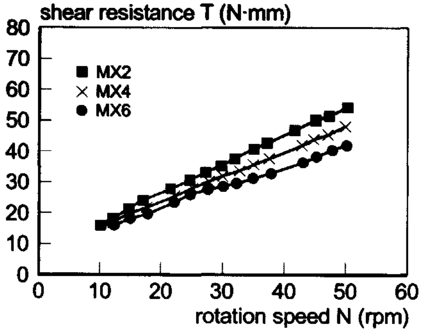


Figure 6.49 T versus N in test series C4

Figure 6.50 shows the comparison between the test series B2 and C4 with regard to the variation of the relative viscosity (*h* [N·mm·min]) and the relative yield value (*g* [N·mm]). In this comparison, it is found that the variation range of *h* for C4 agreed well with the result for B2. This result proves that the dosing of welan gum does not influence the sensitivity for the variation of viscosity depending on the mixing intensity when combined with *SP2*, as discussed in 6.7.4 (2) for the Marsh cone flow time.

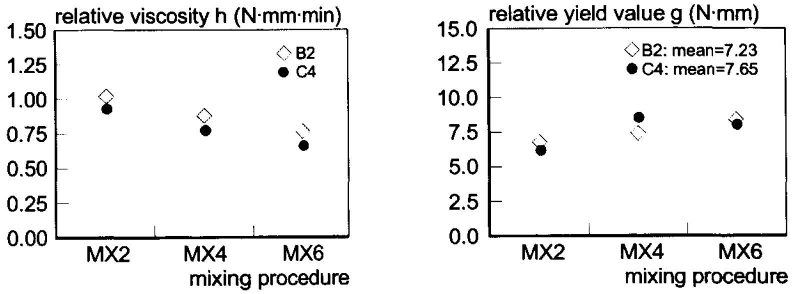


Figure 6.50 Variation of *h* and *g* in test series B2 and C4

On the other hand, the values of *g* were in a small range. The average value of *g* is 7.65 [N·mm] in this series and it is very close to the average value in series B1, B2 and C3 where the same type of superplasticizer was applied.

### 6.7.5 Overall discussions on the effect of welan gum on the behavior of cement paste

According to the test results described before, the effect of welan gum on the behavior of the flowable cement paste and the mixing effect can be summarized as follows. From these results, it can be concluded that the effect of welan gum is different dependent on the type of superplasticizer with which it is combined.

**(1) Influence on the value of $V_w/V_p$ for the target property of cement paste**

Dosing of welan gum raised the value of $V_w/V_p$ for each mixing procedure necessary to obtain the target property of cement paste (see Figures 6.37 and 6.45). In other words, a cement paste with welan gum needs a larger $V_w/V_p$ to realize the target property compared to a non-welan gum mixture when the mixing procedure is fixed. This is the common phenomenon observed for cement pastes both with *SP1* and with *SP2*.

However, in the case of the mixtures with *SP1*, dosing of welan gum makes the mixtures more sensitive to balance the value of $V_w/V_p$ to obtain the target property dependent on the mixing procedures (see Figure 6.37). This tendency is significant especially when the mixing intensity is relatively small. On the other hand, this tendency was not observed for the mixtures with *SP2* (see Figure 6.45).

**(2) Influence on the value of Sp/P for the target property of cement paste**

Dosing of welan gum raised the value of Sp/P for each mixing procedure to obtain the target property of cement paste (see Figures 6.37 and 6.45). In other words, a cement paste with welan gum needs a larger amount of superplasticizer to realize the target property compared to a non-welan gum mixture when the mixing procedure is fixed. This is the common phenomenon for both cement pastes with *SP1* and with *SP2*.

However, in the case of the mixtures with *SP1*, dosing of welan gum makes the mixtures less sensitive to balance the value of Sp/P to obtain the target property dependent on the mixing procedures than in the case of non-welan gum mixtures (see Figure 6.37). On the other hand, this tendency was not observed for the mixtures with *SP2* (see Figure 6.45).

**(3) Influence on the degree of "Mixing Effect 1"**

For the mixtures with *SP1*, it was clarified that the dosing of welan gum worked to increase the degree of "Mixing Effect 1" as discussed in 6.7.2, and the effect did not work for the mixtures with *SP2*.

The value of Sp/P decreased as the mixing intensity increased to realize a constant deformability for the constant proportion of mixtures (see Figure 6.40). This kind of effect was not observed for the mixtures with *SP2*. This phenomenon correlates well with the observations of 6.7.5 (2).

If the amplification of the "Mixing Effect 1" caused by the dosing of welan gum would not have happened, the variation of Sp/P in the series C1 might have resulted in the white dots in Figure 6.51 due to the fundamental effect of welan gum to raise the dosage of superplasticizer. However, the value of the actual Sp/P became smaller than the estimated values when the mixing intensity was large because of the amplified "Mixing Effect 1". As a conclusion, the sensitivity of Sp/P dependent on the mixing procedures became smaller than for the non-welan gum mixtures.

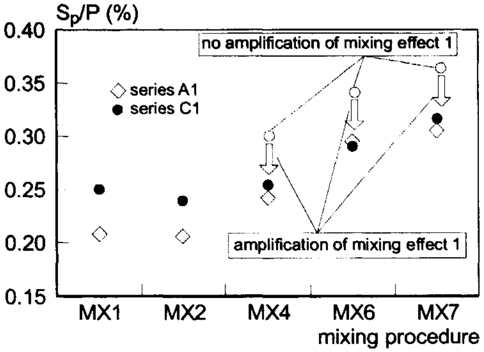


Figure 6.51 Effect of welan gum on "Mixing Effect 1" appearing on Sp/P

On the other hand, the viscosity of the mixture with welan gum tended to be enlarged compared to the non-welan gum mixtures especially when the mixing intensity is relatively small (see Figure 6.41). This kind of effect was not observed for the mixtures with *SP2* (see Figure 6.48). This phenomenon correlates well with the observations of 6.7.5 (1).

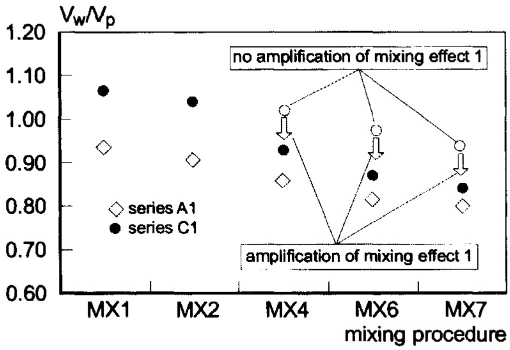


Figure 6.52 Effect of welan gum on "Mixing Effect 1" appearing on $V_w/V_p$

If the amplification of the "Mixing Effect 1" would not have happened, the variation of $V_w/V_p$ in the series C1 might have resulted in the white dots in Figure 6.52 due to the fundamental effect of welan gum to raise the value of $V_w/V_p$. However, the value of actual $V_w/V_p$ became smaller than the estimated values when the mixing intensity was large because of the amplified "Mixing Effect 1". As a conclusion, the sensitivity of $V_w/V_p$ dependent on the mixing procedures became larger than for the non-welan gum mixtures.

According to these observations, it can be understood that the welan gum plays a role to enhance the "Mixing Effect 1". However, it occurs only when it is combined with a polycarboxylic ether based superplasticizer, but not with a naphthalene sulfonate based superplasticizer. This phenomenon implies that this effect of welan gum becomes obvious when the mixing energy consumed is beyond a certain level, and the mixing energy for the paste with *SP2* is lower than that level.

### (4) Influence on the "Mixing Effect 3"

In case of the cement pastes with *SP1*, the air content of the mixture tended to increase as the mixing intensity became large which agrees with the hypothesis of "Mixing Effect 3". This is a common tendency for both mixtures with welan gum and without welan gum. However, the dosing of welan gum showed the influence to reduce the air content compared to non-welan gum mixtures as shown in Figure 6.42. This means that the dosing of welan gum works to reduce the degree of the "Mixing Effect 3".

In the case of the cement pastes with *SP2*, the hypothesized "Mixing Effect 3" is not applicable due to the original characteristics of the air entraining effect of the superplasticizer.

## 6.8 CONCLUSIONS

According to the results obtained in the three test programs A, B and C, the following overall conclusions can be drawn. The details of the evaluation were described in the individual sections.

### (1) Influence of type and intensity of mixing on the proportioning of the target property of cement paste

In order to produce a cement paste mixture with particular properties in the fresh state, the mixture should be designed carefully considering the applied materials' characteristics. However, it was clarified by this study that the mixture composition to achieve certain properties cannot be determined without consideration of the mixing efficiency. In other words, different compositions of mixtures can realize rheologically constant fresh properties by controlling the mixing efficiency even if the same cement, water and superplasticizer are used.

### (2) Verification of the hypothesized "Mixing Effect"

The "Mixing Effect 1 (effect on dispersion of powder particles)" is quite appropriate to explain the behavior of cement paste mixtures with both types of superplasticizer, the polycarboxylic ether type and the naphthalene sulfonate type, as well as for fresh concrete.

The "Mixing Effect 2 (effect on processing powder particles surface)" is not appropriate to explain the behavior of cement paste mixtures with both types of superplasticizer, the polycarboxylic ether type and the naphthalene sulfonate type. This is not compatible with the results of the concrete tests as described in Chapter 5. However, on the basis of the comparison between the results of the paste tests and mortar-concrete tests, it can be concluded that the mixing effect on the surface modification works when the mixing efficiency is much more intensive than the mixing procedure employed in the paste test program, and the action of aggregate grains in mortar and concrete plays a role to cause the effect.

The "Mixing Effect 3 (effect on air bubble generation)" is appropriate to explain the behavior of the cement paste mixtures with a non-AE type of superplasticizer as well as for fresh concrete. However, it is not applicable to the mixtures with a superplasticizer which has a chemical air-entraining effect.

### (3) Evaluation of the effect and function of polycarboxylic ether based superplasticizer

The mixtures with *SP1* were influenced more effectively by the mixing intensity and consumed more energy during mixing than the mixtures with *SP2*. This phenomenon is considered as a proof that the polycarboxylic ether based superplasticizer is helped by the mixing energy to disperse the powder particles and the polymer molecules work to keep the distance of dispersed powder particles by their steric hindrance effect. As a consequence, more energetic mixing makes the cement paste mixtures less viscous very effectively when using this type of superplasticizer.

On the other hand, a larger dosage of *SP1* resulted in not only a more deformable but also a less viscous mixture under the fixed water to cement ratio and the fixed mixing procedure chosen. This result proved that the polycarboxylic ether based superplasticizer influences both the deformability and the viscosity of the cement paste mixtures.

### (4) Evaluation of the effect and function of a naphthalene sulfonate based superplasticizer

The mixtures with *SP2* were influenced less effectively by the mixing intensity and consumed much less energy during mixing than the mixtures with *SP1*. This phenomenon is considered as a proof that the naphthalene sulfonate based superplasticizer can disperse the powder particles spontaneously by its electrostatic repulsion effect and the mixing energy is the secondary force for the powder dispersion. As a consequence, more intensive mixing disperses the cement particles better but its effectiveness is smaller than for a polycarboxylic ether based superplasticizer. This is considered to result in the smaller variation of $V_w/V_p$ for the constant properties of the cement paste. However, the small mixing effect on the particle dispersion reflects significantly on the rheological viscosity of the cement paste and the variation of the viscosity dependent on the mixing procedure is comparable for both types of superplasticizer.

On the other hand, a larger dosage of *SP2* resulted in a more deformable and constant viscosity of the mixture under the fixed water to cement ratio and the fixed mixing procedure. This result proved that the naphthalene sulfonate based superplasticizer influences only the deformability of the cement paste mixtures and the viscosity is not affected.

### (5) Evaluation of the effect and function of welan gum

From the test results, it was clarified that welan gum has a fundamental effect to raise the value of both $V_w/V_p$ and Sp/P to realize the target fresh properties of cement paste mixtures. But its sensitivity, dependent on the mixing intensity, is different according to the type of superplasticizer used. When using the polycarboxylic ether based superplasticizer, mixtures with welan gum are more sensitive on adjusting the value of $V_w/V_p$ and less sensitive on adjusting the value of Sp/P due to the difference in the mixing intensity than non-welan gum mixtures. On the other hand, the welan gum does not affect the sensitivity of adjusting $V_w/V_p$ and Sp/P due to the difference in mixing intensity when using a naphthalene sulfonate based superplasticizer.

The phenomenon described above is related to the influence of welan gum on the mixing effect. When using a polycarboxylic ether based superplasticizer, the dosing of welan gum is believed to increase the degree of the hypothesized “Mixing Effect 1”. However, this effect of welan gum does not happen when it is combined with a naphthalene sulfonate based superplasticizer. This is believed to be related to the difference of the dispersion mechanism and the energy consumption during mixing between both types of superplasticizer.

# CHAPTER 7
# CONCLUSIONS AND SUGGESTIONS

## 7.1 CONCLUSIONS FOR THE RESEARCH PHASE-I

As defined in Chapter 1 this research project consisted of 2 phases. The main purpose of the first phase was to verify the producibility of self-compacting concrete in the Netherlands applying the local materials and conditions.

### 7.1.1 Development of SCC NL-prototype

In Chapter 3, an intensive laboratory test program was carried out aiming at the development of a typical mixture of SCC with materials available on the Dutch market. The Japanese mixture design system qualified as the "general purpose approach" was applied and the following recommendation for the "SCC NL-prototype" was established.

[SCC NL-prototype]

Powder composition : BSC-A 60 %+FA 40 % in volume
Superplasticizer : SP-A&B combining ratio 1:2.5
Fine aggregate : normal river sand, $S_c/M$=40 %
Coarse aggregate : normal river gravel, maximum size=16 mm, $G/G_{lim}$=55-58 %
Welan gum : 0.05 % to water weight (not essential)
Quality control : Slump flow=650±50 mm, V funnel=10±2 -13±2 sec. according to $G/G_{lim}$

An example for a mixture composition was shown in Table 3.9 and the performance of the mixture was demonstrated to the Dutch concrete engineers on 28th October 1997 when the new history of the concrete engineering started in the Netherlands.

As described in 3.2.1 "Mix design philosophy", the reason why the general purpose approach is applied in this project is mainly to help the Dutch concrete engineers in understanding the basic principle of SCC. The recommendation for the "SCC NL-prototype" is aiming at designing a mixture which can be used for general purposes. However, a general purpose mixture is useful for beginners but not always the most rational design. An experienced concrete engineer who understands the basic principle well can make a correct modification of the mixture which is rational and unique for a particular application (see Figure 3.1). The Dutch concrete engineers learned appropriately the basic principle of SCC from the report of this research program. They have developed their own way of thinking for the production and utilization of SCC but it is still based on the same basic principle. Therefore, the Netherlands is now one of the most successful countries in the world regarding the utilization of SCC, even better than Japan. This research program can be regarded as the foundation to develop this position.

### 7.1.2 Utilization of microfillers and their effect on the properties of SCC

In Chapter 4, the utilization of microfillers, silica fume (SF), micronized fly ash (MFA) and coal gasification fly ash (CGFA), aiming at high strength self-compacting concrete with a strength higher than 100N/mm$^2$ after 28 days was studied experimentally.

As a conclusion for the original purpose of this research program, it was found that SF is the best ingredient among the three microfillers tested to raise the strength of the hardened SCC. However, also some extended knowledge was added to the state of information regarding the design of self-compacting concrete.

Firstly, SF and CGFA, which are round-shaped particles much finer than the cement, are quite effective to reduce the viscosity of a fresh concrete with low water to binder ratio. This means that they can improve the workability of high strength concrete which is normally very viscous due to the very low water to binder ratio.

Secondly, SF used tends to spoil the deformability of a fresh concrete and a high amount of superplasticizer is necessary to compensate the loss of deformability. On the other hand, CGFA does not spoil the deformability of fresh concrete. This means that CGFA is expected to be a quite suitable material to enhance the producibility and the workability of SCC using an insufficient intensity of mixer. It is generally recognized that a gravity mixer is not suitable to produce SCC because an SCC mixture mixed by a gravity mixer becomes very viscous and unworkable due to a shortage of mixing energy. CGFA could improve the situation and make the application of gravity mixers, which are popular in the Dutch ready-mixed concrete industry, possible.

Moreover, the information about the effect of microfillers on the properties of fresh SCC obtained in this program encouraged the imagination concerning the "mixing effect" which is the main subject of the second phase of this research project.

## 7.2 CONCLUSIONS FOR THE RESEARCH PHASE-II

The purpose of the second phase of this research project was to provide the necessary information for the further rationalization of the mixture design procedure for SCC, especially the influence of mixing and its dependency on the type of chemical admixture applied.

### 7.2.1 Clarification of the influence of mixing and hypothesizing the mixing effect for SCC

In Chapter 5, the influence of the mixing efficiency on realizing defined properties of fresh SCC was investigated. A number of concrete mixing tests were carried out with varying the mixing procedures and the types of mixers. The most important information obtained from this research program is:

(a) The most adequate value of water to powder volume ratio ($V_w/V_p$) is smaller when the intensity of mixing is larger.
(b) The most adequate dosage of superplasticizer (Sp/P) is larger when the intensity of mixing is larger.

As a consequence of this information, it became clear that an adequate mixture proportion of SCC is dependent on the intensity of the mixer and the mixing procedure even if the properties of the materials are uniform. Moreover, it was also clarified that an adequately designed SCC taking account of the mixing intensity is possible even for a gravity mixer.

Further important information obtained from the program is:

(c) A concrete including welan gum requires a larger increase of $V_w/V_p$ than a non-welan gum concrete to adjust the workability of the fresh concrete for a smaller intensity of mixing.
(d) The naphthalene sulfonate based superplasticizer used required a smaller increase of $V_w/V_p$ than the polycarboxylic ether based superplasticizer used to adjust the workability of the fresh concrete for a smaller intensity of mixing.

This information evidences that the degree of influence of the mixing efficiency on the properties of a fresh SCC is dependent on the type of the chemical admixture applied.

The most important information previously stated under (a) and (b), can be described in an alternative way as follows:

(A) More intensive mixing makes a fresh concrete less viscous when the mixture composition is constant.

(B) More intensive mixing makes a fresh concrete less deformable when the mixture composition is constant.

In order to explain these phenomena, three effects of mixing were hypothesized:

- Mixing Effect 1 : *Effect on the dispersion of powder particles* (see Figure 5.12)
- Mixing Effect 2 : *Effect on processing powder particles' surface* (see Figure 5.13)
- Mixing Effect 3 : *Effect of air bubble generation*

The phenomenon (A) is considered to be caused by the combination of all the three effects. On the other hand, the phenomenon (B) is considered to relate mainly to the "Mixing Effect 2". The small particles of the initial hydration product torn from the surface of binder particles are expected to reduce the viscosity of the mixture as a lubricant, and to spoil the deformability of the mixture due to the excessive adsorption of the superplasticizer. This effect of the particles of the initial hydration product is quite similar to the effect of the silica fume particles confirmed in Chapter 4.

### 7.2.2 Verification of the hypothesized mixing effect focusing on the properties of the flowable cement paste considering the type of chemical admixture

In Chapter 6, the verification of the hypotheses on the mixing efficiency formulated in Chapter 5 was purposed. A very intensive and well-controlled testing program on flowable cement pastes with dosed superplasticizer, and in some cases a viscosity modifying admixture, was performed in order to clarify the influence of mixing on the properties of the paste phase of fresh concrete, because the hypothesized mixing effects were supposed to affect the properties of the paste phase of the fresh SCC.

The results corresponding to the above mentioned phenomenon (A) were obtained very clearly in the paste tests as well. In other words, it was clarified that the different compositions of the cement paste mixtures can realize a set of rheologically constant fresh properties by controlling the mixing efficiency even if the same cement, water and superplasticizer are used. This phenomenon is concluded to be caused by the hypothesized "Mixing Effect 1"and "Mixing

Effect 3" during the mixing of the cement pastes.

On the other hand, the results corresponding to the previously specified phenomenon (B) were not observed in the paste tests. This means that the hypothesized "Mixing Effect 2" does not happen in the cement paste mixing. This allowed an important conclusion regarding the mixing efficiency:

- During the mixing of concrete or a mortar, which includes aggregates in the mixture, a much larger shear energy is supposed to be induced into the paste phase due to the action of solid grains of aggregates than during the mixing of a paste without aggregates. In this situation, the phenomenon hypothesized by the "Mixing Effect 2" must occur and a larger amount of superplasticizer is necessary to obtain adequate properties of the mortar or the concrete than for the paste mixed alone.

Another important discovery in the program of Chapter 6 is the estimation of the difference between the ability of the polycarboxylic ether based superplasticizer used and the naphthalene sulfonate based superplasticizer used.

- A polycarboxylic ether based superplasticizer is helped by the mixing energy to disperse the powder particles and the polymer molecules work to keep the distance between the dispersed powder particles by their steric hindrance effect. As a consequence, more energetic mixing makes the cement paste mixtures less viscous very effectively when using this type of superplasticizer.
- A naphthalene sulfonate based superplasticizer can disperse the powder particles spontaneously by its electrostatic repulsion effect and the mixing energy is the secondary force for the powder dispersion. As a consequence, more intensive mixing disperses the cement particles better but its effectiveness is smaller than for a polycarboxylic ether based superplasticizer.
- A polycarboxylic ether based superplasticizer increases the deformability and decreases the viscosity of the cement paste mixtures. On the other hand, a naphthalene sulfonate based superplasticizer influences only the deformability and the viscosity is not affected.

Furthermore, it was also discovered that the welan gum worked to amplify the "Mixing Effect 1" when it was combined with the polycarboxylic ether based superplasticizer. This effect was not confirmed when it was combined with the naphthalene sulfonate based superplasticizer. Therefore, the users of the welan gum, that means ordinary concrete engineers, have to pay attention to what type of superplasticizer is used in combination, because the welan gum works differently depending on the type of superplasticizer.

## 7.3 SUGGESTIONS

### (1) For concrete engineers, more information is necessary on the performance of chemical admixtures.

In the beginning of this research project, the author aimed to build up a numerical model to describe the mixing efficiency on the properties of self-compacting concrete. It seemed to be possible because the rheological test results correlate well with the electric power consumption of the mixing. However, halfway this idea was abandoned because it became clear that the mixing efficiency is strongly affected by the performance of the materials.

The experimental program in this investigation was confined by a limited variation of the raw materials. The cement was limited to a brand of Dutch blast furnace slag cement. The brands of superplasticizer were also limited. Of course it is possible to establish a numerical model using the results of the experiments, but this might mean that the model is not applicable when materials with other characteristics are used. Furthermore, the influence of the temperature was removed from this experiment but it is a factor which is relevant for the practical production. Therefore, numerical modeling was regarded to be premature and qualitative evaluations were preferred on a basis that was believed to be sufficiently valuable for all the concrete engineers.

Especially, the performance of superplasticizers is various even if they are categorized as being of the same type, e.g. of the polycarboxylic ether based type. Different brand names or different No. of products often show very different effects. New products appear on the market day by day. This is one of the main reasons why the performance of fresh concrete cannot be predicted automatically by a computational method. If more detailed quantitative information about the performance of superplasticizers is provided by the suppliers, this situation may be improved. The more detailed and quantitative information should include as well the compatibility with cement and other powder materials, dependence on the temperature and time progress, influence on the mixing efficiency etc. Then the time is ripe to start thinking on how to design fresh concretes without trial mixing.

### (2) Are superplasticizers developing into the right direction for SCC?

According to the basic principle of self-compacting concrete, high deformability and high segregation resistance must be simultaneously imparted to the fresh concrete. In order to reach this condition, it is essential that the paste phase of the concrete mixture has a high deformability and a high viscosity simultaneously. In order to simultaneously realize these inconsistent performances, generally superplasticizers were used because they are expected to increase the deformability of the paste phase but not to decrease the viscosity. On the other hand, it was obvious that adding water makes the paste more deformable and less viscous. Therefore, the superplasticizer was considered to be an essential component to realize the evolution of concrete. The superplasticizer used in the early-days of SCC was a naphthalene sulfonate based one.

Polycarboxylic ether based superplasticizers became popular some years after the development of SCC in Japan. They had a better dispersibility, a higher water-reducing ability and a longer flowability retention than naphthalene sulfonate based ones. Therefore, such superplasticizers are useful for concretes with a low water to binder ratio, e.g. high strength concrete. Also for SCC they seemed to be quite useful. Actually, the polycarboxylic ether based superplasticizers turned out to have many advantages and soon got popular as an ingredient for SCC. However, most of the concrete engineers did not notice that this type of superplasticizer increases the deformability but simultaneously decreases the viscosity of the paste of the concrete as well. As a consequence, the SCC mixtures required an increasing amount of powder materials in order to maintain sufficient segregation resistance.

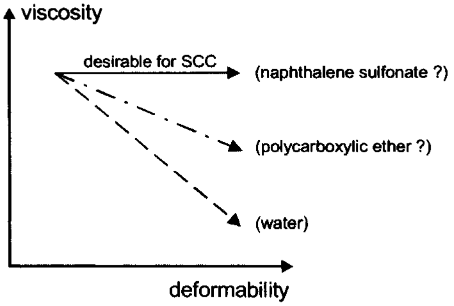


Figure 7.1 Image of the role of superplasticizers and water in fresh concrete

Figure 7.1 shows an image of the role of superplasticizers and water in fresh concrete. Minimum viscosity loss is desirable for the self-compactability of fresh concrete. However, the polycarboxylic ether based superplasticizer developed away from the original principle. It is no doubt that this type of superplasticizer is suitable for high strength concrete because it requires a very low water to binder ratio to realize a high strength. The viscosity reducting effect of the superplasticizer works to improve the workability. However, self-compacting concrete does not always require a high strength. The amount of cement or powder materials should be as small as possible for economical reasons as long as adequate viscosity for segregation resistance can be obtained. In this situation, the viscosity reducting effect of a superplasticizer is undesirable.

The undesirable performance of a kind of superplasticizer as an ingredient of SCC has become clear in this research project through intensive and well-controlled experiments. This information is expected to be a good suggestion for the development of a new type of superplasticizer for the next generation.

Finally, all the information obtained in this research project is believed to be a help for the concrete engineers who are eager to utilize SCC effectively and correctly for their own society.

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# NOTATIONS AND SYMBOLS

| | | |
|---|---|---|
| A | abbreviation for air | |
| A | volume of the air in the concrete | $[m^3/m^3]$ |
| AE | abbreviation for air entraining | |
| $B_h$ | filling height of the box test | [mm] |
| BSC | abbreviation for blast furnace slag cement | |
| CGFA | abbreviation for coal gasification fly ash | |
| D | share rate | [1/s] |
| $E_m$ | inclination of the line between $V_w/V_p$ and $\Gamma_m$ of the mortar flow test | [ -- ] |
| $E_p$ | inclination of the line between $V_w/V_p$ and $\Gamma_p$ of the paste flow test | [ -- ] |
| F | filling ratio of the filling vessel test | [%] |
| F-- | abbreviation for mixing by forced pan mixer in chapter 5 (--: total mixing time;min) | |
| FA | abbreviation for fly ash | |
| FAC | abbreviation for fly ash cement | |
| fc | compressive strength | [N/mm] |
| G | abbreviation for coarse aggregate | |
| $g$ | relative yield value | [N·mm] |
| G | volume of the coarse aggregate in the concete | $[m^3/m^3]$ |
| G-- | abbreviation for mixing by gravity tilting mixer in chapter 5 (--: total mixing time;min) | |
| $G/G_{lim}$ | ratio of the coarse aggregate volume in the concrete except the air to its solid volume (packing density) | [ -- ] |
| $G_{lim}$ | solid volume ratio (packing density) of the coarse aggregate | [ -- ] |
| $h$ | relative viscosity | [N·mm·min] |
| $h_1$ | filling height of the filling vessel test at the back end | [mm] |
| $h_2$ | filling height of the filling vessel test at the front end | [mm] |
| $\Delta h$ | gap of filling height of the filling vessel test ($h_1$-$h_2$) | [mm] |
| LS | abbreviation for limestone powder | |

| | | |
|---|---|---|
| MFA | abbreviation for micronized fly ash | |
| MX- | abbreviation for mixing procedure in chapter 6 | |
| N | rotational speed | [rpm] |
| P | load | [N] |
| P.C.A, P.C.B | power consumption | [J] |
| PC | abbreviation for Portland cement | |
| r | average flow diameter of the mortar flow test | [mm] |
| $r_0$ | bottom diameter of the mortar flow cone (=100) | [mm] |
| $R_c$ | relative flow speed of the V-funnel test | [ -- ] |
| $R_m$ | relative flow speed of the mortar funnel test | [ -- ] |
| $R_{m0}$ | relative flow speed of the mortar funnel test when $V_w/V_p = \gamma_0$ | [ -- ] |
| $R_{mTG}$ | target value of $R_m$ adequate for SCC (=1.0) | [ -- ] |
| S | abbreviation for fine aggregate | |
| S | volume of the fine aggregate in the concete | [$m^3/m^3$] |
| $S/S_{max}$ ($S/S_{lim}$) | ratio of the sand volume in the mortar to its solid volume (packing density) | [ -- ] |
| $S_c/M$ | ratio of the fine aggregate(>0.09 or 0.125mm) volume in the mortar expect the air | [ -- ] |
| SCC | abbreviation for self compacting concrete | |
| SF | abbreviation for silica fume | |
| SP | abbreviation for superplasticizer | |
| Sp/P | dosage ratio of superplasticizer to powder weight | [%] |
| t | flow time of V-funnel test or mortar funnel test | [s] |
| T | share resistance | [N·mm] |
| $V_s$ | volume of the sand in the mortar | [$m^3/m^3$] |
| $V_w/V_p$ | water to powder volume ratio | [ -- ] |
| $V_{w1}/V_p$ | first charge of water to powder volume ratio | [ -- ] |
| W | abbreviation for water | |
| W | water content | [$kg/m^3$] |
| $W_1$ | first charge of water for double mixing | [$kg/m^3$] |
| $W_2$ | second charge of water for double mixing | [$kg/m^3$] |
| $\alpha$ | premium factor to adjust the adequate $V_w/V_p$ due to mixing efficiency | [ -- ] |

| | | |
|---|---|---|
| $\beta_m$ | water retaining ratio of the powder and the sand in the mortar | [ -- ] |
| $\beta_p$ | water retaining ratio of the powder in the paste | [ -- ] |
| $\beta_s$ | apparent water retaining ratio of the sand | [ -- ] |
| $\gamma_0$ | initial value of $V_w/V_p$ to determine the target value ($\gamma_{TG}$) | [ -- ] |
| $\gamma_a$, $\gamma_b$, $\gamma_c$ | adequate value of $V_w/V_p$ for the powder combination (a), (b), (c) | [ -- ] |
| $\Gamma_m$ | relative flow area of the mortar flow test | [ -- ] |
| $\Gamma_{m0}$ | relative flow area of the mortar flow test when $V_w/V_p = \gamma_0$ | [ -- ] |
| $\Gamma_{mTG}$ | target value of $\Gamma_m$ adequate for SCC (=5.0) | [ -- ] |
| $\Gamma_p$ | relative flow area of the paste flow test | [ -- ] |
| $\gamma_{TG}$ | target value of $V_w/V_p$ adequate for SCC | [ -- ] |
| $\eta$ | dynamic viscosity of Newtonian fluids | [$N \cdot s/m^2$] |
| $\eta_B$ | dynamic viscosity of Bingham fluids | [$N \cdot s/m^2$] |
| $\kappa_{sf}$ | fine particle (<0.09 or 0.125mm) ratio in the fine aggregate | [ -- ] |
| $\tau$ | share stress | [$N/m^2$] |
| $\tau_f$ | yield value of Bingham fluids | [$N/m^2$] |

# APPENDIX

## Results of test on flowable cement paste in chapter 6

Results of Test Series A1

| Case No. |  | ***SP1 &*** |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | ***MX1*** | ***MX2*** | ***MX3*** | ***MX4*** | ***MX5*** | ***MX6*** | ***MX7*** |
| $V_w/V_p$ |  | 0.935 | 0.905 | 0.900 | 0.860 | 0.830 | 0.815 | 0.800 |
| Sp/P (%) |  | 0.208 | 0.206 | 0.210 | 0.242 | 0.274 | 0.295 | 0.305 |
| Mini-Slump (ave.) (mm) |  | ***109.0*** | ***110.3*** | ***110.0*** | ***110.0*** | ***111.3*** | ***111.3*** | ***110.3*** |
| Marsh cone time (sec.) |  | ***45.2*** | ***43.4*** | ***42.0*** | ***42.8*** | ***43.5*** | ***44.3*** | ***44.5*** |
| unit weight (g) |  | 1974 | 1974 | 1964 | 1984 | 1971 | 1962 | 1958 |
| Air content (%) |  | 1.46 | 2.24 | 2.86 | 2.93 | 4.40 | 5.22 | 5.82 |
| Bleeding (ml/100ml) |  | 1.6 | 1.3 | 1.5 | 0.8 | 0.6 | 0.5 | 0.3 |
| power consumption (J) | A | 11604 | 18329 | 16126 | 23837 | 33071 | 42924 | 56217 |
|  | B | 831 | 1600 | 2459 | 6672 | 12295 | 18892 | 27836 |
| relative viscosity (N·mm·min) |  | 0.795 | 0.896 | 0.839 | 0.808 | 0.933 | 0.820 | 0.879 |
| relative yield value (N·mm) |  | 5.96 | 3.82 | 4.79 | 4.80 | 3.69 | 5.22 | 4.74 |

Results of Test Series A2

| Case No. | | ***SP1 &*** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ***MX1*** | ***MX2*** | ***MX3*** | ***MX4*** | ***MX5*** | ***MX6*** | ***MX7*** |
| $V_w/V_p$ | | ***0.860*** | | | | | | |
| Sp/P (%) | | 0.250 | 0.246 | 0.246 | 0.242 | 0.245 | 0.244 | 0.246 |
| Mini-Slump (ave.) (mm) | | ***108.8*** | ***110.3*** | ***109.5*** | ***110.0*** | ***110.3*** | ***109.8*** | ***110.0*** |
| Marsh cone time (sec.) | | 57.0 | 48.4 | 47.5 | 42.8 | 40.1 | 39.7 | 35.1 |
| unit weight (g) | | 2006 | 1999 | 1996 | 1984 | 1960 | 1946 | 1927 |
| Air content (%) | | 1.86 | 2.20 | 2.34 | 2.93 | 4.10 | 4.79 | 5.72 |
| **Bleeding (ml/100ml)** | | 0.9 | 1.0 | 1.8 | 0.8 | 1.0 | 1.1 | 0.5 |
| power consumption (J) | A | 13371 | 20806 | 18931 | 23837 | 28828 | 33723 | 41063 |
| | B | 2734 | 3922 | 5238 | 6672 | 9360 | 11163 | 12783 |
| relative viscosity (N·mm·min) | | 1.300 | 1.016 | 0.989 | 0.808 | 0.746 | 0.735 | 0.629 |
| relative yield value (N·mm) | | 4.61 | 4.77 | 5.00 | 4.80 | 4.48 | 4.88 | 4.78 |

Results of Test Series A3

| Case No. | | ***SP1 &*** ***MX4*** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $V_w/V_p$ | | ***0.860*** | | | | | | |
| Sp/P (%) | | 0.215 | 0.220 | 0.225 | 0.235 | 0.242 | 0.255 | 0.265 |
| Mini-Slump (ave.) (mm) | | 92.5 | 96.3 | 103.3 | 107.0 | 110.0 | 114.0 | 118.5 |
| Marsh cone time (sec.) | | 72.4 | 61.7 | 52.8 | 46.7 | 42.8 | 39.9 | 37.1 |
| unit weight (g) | | 2000 | 1999 | 1990 | 1977 | 1984 | 1992 | 1980 |
| Air content (%) | | 2.16 | 2.21 | 2.65 | 3.30 | 2.93 | 2.55 | 3.14 |
| Bleeding (ml/100ml) | | 1.0 | 1.0 | 1.0 | 1.1 | 0.8 | 1.4 | 1.2 |
| power consumption (J) | A | 25285 | 25041 | 24059 | 23562 | 23837 | 22873 | 21454 |
| | B | 9149 | 7889 | 8219 | 7414 | 6672 | 6230 | 5798 |
| relative viscosity (N·mm·min) | | 1.331 | 1.218 | 1.048 | 0.941 | 0.808 | 0.826 | 0.732 |
| relative yield value (N·mm) | | 11.70 | 9.96 | 6.51 | 5.91 | 4.80 | 4.61 | 2.96 |

Results of Test Series B1

| Case No. | | ***SP2 &*** | | | | |
|---|---|---|---|---|---|---|
| | | ***MX1*** | ***MX2*** | ***MX4*** | ***MX6*** | ***MX7*** |
| $V_w/V_p$ | | 0.960 | 0.955 | 0.935 | 0.925 | 0.915 |
| Sp/P (%) | | 1.190 | 1.180 | 1.240 | 1.330 | 1.310 |
| Mini-Slump (ave.) (mm) | | ***110.0*** | ***109.0*** | ***109.5*** | ***112.0*** | ***110.0*** |
| Marsh cone time (sec.) | | ***44.9*** | ***44.8*** | ***43.8*** | ***42.6*** | ***46.0*** |
| unit weight (g) | | 1913 | 1921 | 1947 | 1942 | 1965 |
| Air content (%) | | 4.22 | 3.94 | 3.14 | 3.65 | 2.79 |
| Bleeding (ml/100ml) | | 1.1 | 1.3 | 1.2 | 1.0 | 1.0 |
| power consumption (J) | A | 10816 | 16871 | 19438 | 26971 | 33198 |
| | B | 469 | 570 | 2714 | 4262 | 4237 |
| relative viscosity (N·mm·min) | | 0.864 | 0.916 | 0.879 | 0.854 | 0.786 |
| relative yield value (N·mm) | | 9.07 | 7.49 | 7.48 | 6.61 | 9.14 |

Results of Test Series B2

| Case No. | | ***SP2 &*** | | | | |
|---|---|---|---|---|---|---|
| | | ***MX1*** | ***MX2*** | ***MX4*** | ***MX6*** | ***MX7*** |
| $V_w/V_p$ | | ***0.935*** | | | | |
| Sp/P (%) | | 1.240 | 1.240 | 1.240 | 1.240 | 1.240 |
| Mini-Slump (ave.) (mm) | | ***110.3*** | ***109.5*** | ***109.5*** | ***110.8*** | ***110.0*** |
| Marsh cone time (sec.) | | 53.6 | 50.1 | 43.8 | 41.6 | 36.4 |
| unit weight (g) | | 1945 | 1941 | 1947 | 1948 | 1963 |
| Air content (%) | | 3.24 | 3.44 | 3.14 | 3.09 | 2.35 |
| Bleeding (ml/100ml) | | 1.3 | 1.0 | 1.2 | 1.2 | 1.0 |
| power consumption (J) | A | 12308 | 18215 | 19438 | 25640 | 32303 |
| | B | 1965 | 2494 | 2714 | 3761 | 4949 |
| relative viscosity (N·mm·min) | | 1.107 | 1.025 | 0.879 | 0.765 | 0.629 |
| relative yield value (N·mm) | | 6.13 | 6.80 | 7.48 | 8.34 | 7.42 |

Results of Test Series B3

| Case No. | | ***SP2 &<br>MX4*** | | |
|---|---|---|---|---|
| $V_w/V_p$ | | ***0.935*** | | |
| Sp/P (%) | | 1.160 | 1.240 | 1.320 |
| Mini-Slump (ave.) (mm) | | 101.0 | 109.5 | 119.0 |
| Marsh cone time (sec.) | | 46.6 | 43.8 | 40.8 |
| unit weight (g) | | 1950 | 1947 | 1950 |
| Air content (%) | | 2.97 | 3.14 | 3.02 |
| Bleeding (ml/100ml) | | 1.2 | 1.2 | 0.9 |
| power consumption (J) | A | 18668 | 19438 | 17738 |
| | B | 2146 | 2714 | 1580 |
| relative viscosity (N·mm·min) | | 0.816 | 0.879 | 0.864 |
| relative yield value (N·mm) | | 9.96 | 7.48 | 6.72 |

Results of Test Series C1

| Case No. | | ***SP1W &*** | | | | |
|---|---|---|---|---|---|---|
| | | ***MX1*** | ***MX2*** | ***MX4*** | ***MX6*** | ***MX7*** |
| $V_w/V_p$ | | 1.065 | 1.040 | 0.930 | 0.870 | 0.840 |
| Sp/P (%) | | 0.250 | 0.240 | 0.254 | 0.290 | 0.317 |
| Mini-Slump (ave.) (mm) | | ***110.8*** | ***110.8*** | ***109.8*** | ***110.5*** | ***112.0*** |
| Marsh cone time (sec.) | | ***42.3*** | ***45.9*** | ***46.5*** | ***46.6*** | ***46.5*** |
| unit weight (g) | | 1902 | 1934 | 1966 | 1964 | 1936 |
| Air content (%) | | 2.00 | 0.93 | 2.02 | 3.66 | 5.82 |
| Bleeding (ml/100ml) | | 2.0 | 2.0 | 1.0 | 1.1 | 0.7 |
| power consumption (J) | A | 11025 | 16529 | 21467 | 35924 | 50742 |
| | B | 390 | 414 | 5144 | 13756 | 22058 |
| relative viscosity (N·mm·min) | | 0.758 | 0.859 | 0.901 | 0.907 | 0.909 |
| relative yield value (N·mm) | | 5.12 | 5.90 | 6.42 | 5.07 | 4.97 |

Results of Test Series C2

| Case No. | | SP1W & | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ***MX1*** | ***MX2*** | ***MX3*** | ***MX4*** | ***MX5*** | ***MX6*** | ***MX7*** |
| $V_w/V_p$ | | ***0.930*** | | | | | | |
| Sp/P (%) | | 0.302 | 0.271 | 0.270 | 0.254 | 0.258 | 0.254 | 0.240 |
| Mini-Slump (ave.) (mm) | | ***109.8*** | ***109.0*** | ***111.0*** | ***109.8*** | ***111.5*** | ***111.3*** | ***111.0*** |
| Marsh cone time (sec.) | | 80.0 | 61.8 | 50.1 | 46.5 | 39.2 | 37.8 | 37.2 |
| unit weight (g) | | 1987 | 1976 | 1978 | 1966 | 1945 | 1944 | 1935 |
| Air content (%) | | 0.98 | 1.50 | 1.40 | 2.02 | 3.07 | 3.12 | 3.55 |
| Bleeding (ml/100ml) | | 1.0 | 1.6 | 1.4 | 1.0 | 1.5 | 1.6 | 1.1 |
| power consumption (J) | A | 13820 | 17760 | 17148 | 21467 | 25842 | 30027 | 37351 |
| | B | 3523 | 1966 | 3395 | 5144 | 5996 | 7117 | 9244 |
| relative viscosity (N· mm·min) | | 1.393 | 1.169 | 1.007 | 0.901 | 0.693 | 0.657 | 0.686 |
| relative yield value (N·mm) | | 5.45 | 5.70 | 5.71 | 6.42 | 4.77 | 4.85 | 5.64 |

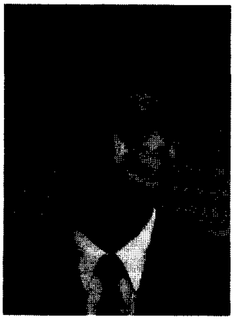
Results of Test Series C3

| Case No. | | ***SP2W &*** | | |
|---|---|---|---|---|
| | | ***MX2*** | ***MX4*** | ***MX6*** |
| $V_w/V_p$ | | 1.000 | 0.980 | 0.965 |
| Sp/P (%) | | 1.290 | 1.380 | 1.480 |
| Mini-Slump (ave.) (mm) | | ***111.0*** | ***109.8*** | ***111.5*** |
| Marsh cone time (sec.) | | ***44.8*** | ***46.3*** | ***46.1*** |
| unit weight (g) | | 1892 | 1928 | 1948 |
| Air content (%) | | 4.33 | 3.01 | 1.76 |
| Bleeding (ml/100ml) | | 0.5 | 0.5 | 0.3 |
| power consumption (J) | A | 15882 | 17238 | 25037 |
| | B | 245 | 1844 | 3375 |
| relative viscosity (N·mm· min) | | 0.796 | 0.776 | 0.785 |
| relative yield value (N·mm) | | 7.10 | 8.62 | 8.50 |

Results of Test Series C4

| Case No. | | *SP2W &* | | |
|---|---|---|---|---|
| | | ***MX2*** | ***MX4*** | ***MX6*** |
| $V_w/V_p$ | | ***0.980*** | | |
| Sp/P (%) | | 1.380 | 1.380 | 1.380 |
| Mini-Slump (ave.) (mm) | | ***112.0*** | ***109.8*** | ***110.0*** |
| Marsh cone time (sec.) | | 51.6 | 46.3 | 40.3 |
| unit weight (g) | | 1906 | 1928 | 1929 |
| Air content (%) | | 4.12 | 3.01 | 2.96 |
| Bleeding (ml/100ml) | | 0.6 | 0.5 | 0.4 |
| power consumption (J) | A | 15868 | 17238 | 24118 |
| | B | 741 | 1844 | 2644 |
| relative viscosity (N·mm·min) | | 0.938 | 0.776 | 0.661 |
| relative yield value (N·mm) | | 6.25 | 8.62 | 8.08 |

# Curriculum Vitae



Kazunori Takada

Date of birth: April 1st, 1968.
Place of birth: Tokyo, Japan.
Nationality: Japanese.

## *Education and academic experience*

| | |
|---|---|
| 1986 | Graduated Urawa High School, Saitama Prefecture, Japan |
| 1990 | Graduated civil engineering department, University of Tokyo, Japan |
| 1992 | Graduated master course in civil engineering, University of Tokyo, Japan |
| 1996-1998 | Guest researcher, Faculty of Civil Engineering, Delft University of Technology, The Netherlands. |

## *Work experience*

| | |
|---|---|
| 1992-1999 | Research engineer, Technical Research Institute, Kajima Corporation, Japan |
| 1999-2002 | Deputy manager at construction site office, Tokyo branch, Kajima Corporation, Japan |
| 2002-2003 | Senior research engineer, Technical Research Institute, Kajima Corporation, Japan |
| 2003- | Deputy manager, Office of corporate strategy, Corporate planning division, Kajima Corporation, Japan |

## Participation to committees

| | |
|---|---|
| 1995-1997 | Technical committee on autogenous shrinkage of concrete, JCI |
| 1997-2000 | Technical committee on self compacting concrete, RILEM |
| 1998 | Scientific committee of 1st Int. symposium on Self Compacting Concrete, Stockholm |
| 2001 | Scientific committee of 2nd Int. symposium on Self Compacting Concrete, Tokyo |
| 2001-2004 | Research committee on contract system of public works, JSCE |

## Contact

k-takada@kajima.com

http://www.kajima.co.jp/welcome.htm

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