Bulletin No. 8

Ultra High Performance Concrete

Published By:

RMCMA

Ready Mixed Concrete Manufacturers' Association (India)

March' 2023

PRESIDENTS' MESSAGE

Concrete is a versatile material and can be designed for high performance and durability. With emergence of various advanced materials, concrete technologists have been improvising concrete properties to enhance the performance for various kinds of application. Ultra High Performance Concrete (UHPC) is one such enhanced material which has a tremendous potential for solving critical construction challenges. It is a high performance and efficient alternative material for making lighter and intricately designed building facades, monuments and thin shell structures. While many usages of this material have been known in various parts of the world, the product has now become commercially available in India.

UHPC possesses characteristics which make it a suitable construction solution for many critical requirements. UHPC consists of sand, cement, and silica fume in a dense, low water-cement ratio mix. Compressive strengths beyond 150 MPa, along with low permeability can be achieved depending on the curing process. To improve ductility, micro-steel fibers or fiberglass fibers are added, thus imparting unique performance characteristics. This material ensures that the durability, low-porosity, resilience and ductility stand the test of time, while improving the energy efficiency of the buildings.
It is also a highly mouldable material, allowing us to produce customized, precast shapes to suit any building's specific location and resist sun intensity.

This material offers architects and designers a new alternative for lightweight, durable structures with slim, streamlined shapes. This results in considerably lower consumption of materials, therefore lighter buildings and faster construction, while at the same time offering greater functionality and durability. The mechanical performances of UHPCs enable façade elements to be much lighter and very easy to implement. UHPC has a potential to be the technology of the future. I congratulate RMCMA for this contemporary publication and wish the readers of this bulletin a great reading and learning experience.

Er. Ramesh Joshi
(President, RMCMA)

1. INTRODUCTION:

Present times are witnessing construction of super tall buildings (200 m and above), long span bridges, high speed rail network, sea-links and similar other structures in private and public sectors in various parts of India. At the same time, sustainability, optimisation of construction materials and reducing carbon footprints to mitigate the adverse effects of climate change pose new challenges before the engineers. It has therefore become of paramount importance to find viable and effective alternative construction materials and technologies to resolve these challenges. The new-age construction materials shall encompass maximum strength within least amount of material volume for sustainability and minimising carbon footprints and long term durability. To meet these objectives, engineers and researchers in Europe have developed new wonder material in the form of Ultra High Performance Concrete (UHPC). Though, the concept of UHPC was conceived about 45 years back but the serious work for developing UHPC was started during 1990s.

The U.S. Federal Highway Administration in its technical report [1] defines "UHPC as cementitious composite material composed of an optimised gradation of granular constituents, a water-to-binder ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement".

The mechanical properties of UHPC include compressive strength greater than 150 MPa and sustained post cracking tensile strength greater than 5 MPa. UHPC is densely packed material using micro and sometimes nano size particles. This imparts it not only high strength but also high durability. High ductility and flexural strength in UHPC come from the use of micro thin (0.2 mm x 13 mm) steel fibers ranging upto almost 3% of UHPC volume. In this bulletin, constituent materials, mix proportioning, production, durability characteristics and applications of UHPC are discussed.

2. DEVELOPMENT STAGES OF UHPC:

The concrete technology progressed slowly during the 1960's with the maximum compressive strength of 20-30 MPa. The concrete compressive strength more than doubled during the next decades 45-60 MPa and it reached to its plateau at about 60 MPa in early 1970's. The availability of water reducers at that time failed to reduce the w/b ratio any further. During 1980's with the availability of high range water reducer, called superplasticizer (SP) were able to progressively reduce w/b ratio to about 0.3. Reducing the w/b below this level was achieved by Bache [2] reported that with high doses of SP and silica fume, it was possible to reduce w/b to 0.16. Concrete compressive strength of upto 280 MPa was achieved through compacted granular materials by optimising the grain size distribution of the granular skeleton. These efforts resulted in the creation of a material with a minimum number of defects such as micro cracks and interconnected pore spaces to achieve ultimate strength and durability enhancement.

These technological breakthroughs have led to the development of ultra-high performance Portland cement based materials that present remarkable mechanical properties. In general, the developments of UHPC can be described in four stages namely before 1980s, 1980s, 1990s, and after 2000. Before 1980s, due to the lack of advancement in technology, production of UHPC was limited at experimental stage only to the labs. At this time, researchers tried different kind of methods to achieve denser and more compact concrete to improve its strength. It was reported that, with vacuum mixing and temperature curing, the compressive strength of concrete could go up to 510 MPa [3]. However, the preparation was very difficult and energy-consuming and impracticable to translate at construction sites.

In the early 1980s, the micro defect free cement (MDF) was invented [4, 5]. The MDF approach uses polymers to fill up the pores and to remove all the defects in cement paste. This process requires specific manufacturing conditions, including laminating of the material by passing it through rollers. MDF concrete can have compressive strength of upto 200 MPa. However, expensive raw material, complicated preparation process, large creep, and brittleness had limited its applications. After the invention of MDF, dense silica particle cement (DSP) was prepared in Denmark by Bache [2]. Unlike MDF, the preparation of DSP does not require extreme manufacturing conditions. Improving the particle packing density eliminated the defects in DSP. The DSP concrete contains high dose amount of SP and silica fume, it also uses heat and pressure curing. The maximum compressive strength of DSP can reach upto 345 MPa. However, despite the ultra-high strength increase, these materials become more 'brittle'. Steel fibers were introduced in the 1980s to improve the brittleness of DSP concretes. This type of steel fiber supplemented concrete can be considered as precursor of present day UHPC. This development led to two new types of concretes, CRC and slurry infiltrated fiber concrete (SIFCON), which exhibit excellent mechanical properties and durability. However, due to the lack of effective SP, both CRC and SIFCON have workability issues, which hinder in-situ applications [5, 6].

In 1990s; Richard et al. [7] used ingredients with increased fineness and reactivity to develop reactive powder concrete

(RPC) via thermal treatment. RPC is a major milestone in the development of UHPC. RPC is characterized by high binder content, very high cement content, very low w/c, use of silica fume (SF), fine quartz powder, quartz sand, SP and steel fibers [7, 8, 9]. These steel fibers are generally 12.5 mm in length and 180 micron in diameter [7]. The coarse aggregates are eliminated for homogeneity enhancement of the matrix. The compressive strength of RPC ranges from 200 MPa to 800 MPa. RPC shows very excellent workability which is an advantage and the most essential requirement for large-scale applications. In the late 1990s, the first UHPC developed through RPC technology was commercialized under the name Ductal in US. In 1997, the world's first RPC structure was built for pedestrian bridge in Sherbrooke, Canada [10, 11]. It was the first time that RPC had been used for building up the whole structure. Despite the successful application of RPC, its application remained limited due to its expensive material and production cost.

Table 1.
Typical Mix Proportions of UHPC (DUCTAL)

S. No.	Ingredient	Weight/m^3 in kg	% by Weight
1.	Cement (OPC)	712	28.5
2.	Fine Sand	1020	40.8
3.	Silica Fume	231	9.3
4.	Glass Powder / Quartz Sand	211	8.4
5.	HR WR	30.7	1.2
6.	Accelerator	30.0	1.2
7.	Steel Fibers	156	6.2
8.	Water	109	4.4

Sherbrooke Pedestrian Bridge in Canada

From year 2000 onwards, much progress has been made on the development of UHPC. With further developments of the concrete technology, it was realized that besides the high strength, the concrete should also have other excellent properties, which led to the term UHPC and UHPFRC [12]. A wide range of new concrete formulations has been developed to cover an increased number of applications. At present, sustainable UHPC formulations are proposed and practiced by various researchers aimed to lower both its material and initial cost. Supplementary cementitious materials, such as fly ash (FA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA) and Silica Fume are used for replacing part of cement in the effort of producing sustainable UHPC and reducing cement content. Furthermore, UHPC can be prepared with normal temperature curing without sacrificing its properties. Due to emergence of environmental friendly UHPC with relatively low cost, its applications are increasing in variety of structures.

3. CONSTITUENT MATERIALS:

UHPC in general consists of a combination of Portland Cement, fine sand, silica fume, high range water reducing admixtures (PC based) glass powder, steel fibers and water. In UHPC, normally coarse aggregates are not used but sometimes smaller size aggregates of proper quality are used. Graybeal [13] has mentioned that the cement should have moderate fineness and Tricalcium Aluminate (C3A) content shall be below 8%. Sand shall be without any silt or organic impurities with maximum grain size of 0.8 mm. Silica fume conforming IS: 15388 – 2003 with very low carbon content and approximating 25% of weight of cement is used. Glass powder (1.7 µm) approximating 25% of weight of cement and high water reducing admixtures (water reducing capacity about 40% and steel fibers (0.2 mm x 15mm at 2.5% to 3%) by volume of UHPC are used. The water binder ratio of UHPC is kept in the range of 0.12 to 0.16. The water for mixing and curing of UHPC shall conform to IS: 456 – 2000.

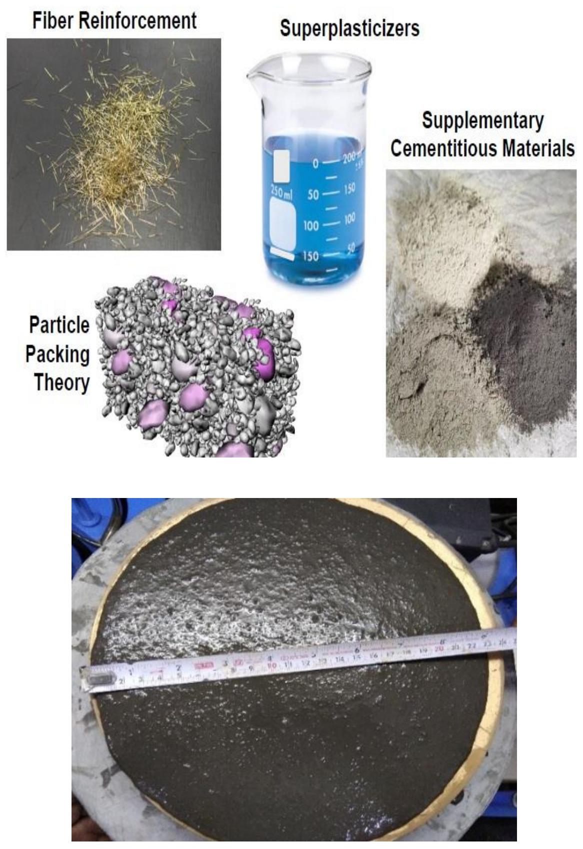
A good percentage of cement typically is left unhydrated in UHPC. The degree of hydration of cement in UHPC varies between 50% to 55%. It poses a challenge for the mix designer to increase the hydration of cement in the mix without compromising on the mechanical and durability characteristics of the mix. To assess the hydration degree of cement, thermal tests are conducted using a Netzch Simultaneous Analyser to obtain the thermogravimetric and differential scanning calorimetry curves of the UHPC pastes. It has been found that degree of hydration of cement can be increased to 60% to 67% by adding limestone/quartz filler in the range of 20% to

25% respectively. Therefore with the perspective of designing optimal mixes the use of filler materials is made in specific mixes.

4. MIX PROPORTIONING OF UHPC:

Mix proportioning of UHPC follows similar sequence as for HPC. The major difference being absence of coarse aggregates in UHPC and addition of fine sand (0.8 mm) at approximate 1.5 times the weight of cement. In trial mixes silica fume and glass powder or ground quartz each is used about 20 to 25% of weight of cement. The steel fibers are used 1.5% to 3% by volume. Water to binder ratio (w/b) is kept in the range of 0.12 to 0.16. The typical mix proportions of UHPC proprietary mix called DUCTAL in USA, is given in Table – 1. The mix proportion in Table – 1 gives compressive strength at 28 days in the range of 170 – 240 MPa and flexural strength of 25 to 60 MPa.

UHPC mixes are normally self-levelling and self-compacting. The workability therefore is measured as fluidity or flowability of concrete by using a flow table. The flow tests are based on ASTM C1856-17 and uses a small flow cone. Typical flows are between 200 mm to 250 mm.



UHPC Ingredients and free Flowing Property of UHPC

5. UHPC PRINCIPLES AND COMPOSITION:

UHPC production over the past 15 years have seen remarkable advances. The compressive strength of UHPC in field application has reached upto 200 MPa. The practical breakthrough came after the development of efficient SP that enabled the production of easy flowing concrete with a high proportion of optimally packed ultrafine particles to minimize the composite porosity using extremely low w/b ratio. The basic principle in designing UHPC are summarised as follows;

1. Minimizing composite porosity by optimizing the granular mixture through a wide distribution of powder and reducing the w/b.

2. Enhancement of the microstructure by the post set heat treatment to speed up the pozzolanic reaction of SF and to increase mechanical properties.

3. Improvement of homogeneity by eliminating coarse aggregate resulting in a decrease in the mechanical effects of heterogeneity.

4. Increase in ductile behaviour by adding adequate volume of small steel fibers.

5. Use of high dose of efficient superplasticizer.

Steel fibers help to improve both tensile strength and ductility of the concrete.

6. MIXTURE DESIGN FOR UHPC:

Mixture design is a selection of raw materials in optimum proportions to provide concrete with required properties in fresh and hardened state for particular applications. The design of UHPC aims to achieve a densely compacted cementitious matrix with good workability and strength. Various models have been reported for the mixture design of UHPC. For instance, Larrad and Sedran [15] proposed a linear packing density model (LPDM) for the mixture design of UHPC. However, this model was limited as it was unable to address the relationship between materials proportions and packing density due to its linear nature. This model was later improved considering the virtual density theory known as solid suspension model (SSM) [15]. This new model allows the production of a fluid mortar with a 0.14 w/b ratio and a compressive strength of 236 MPa with a 4-day curing at 90 °C. D. Larrad and his team once again did further improvement on the latter model based on the compaction index concept and virtual packing density. This third generation of packing model known as compressible packing model (CPM) was proposed for UHPC design [16]. Park et al. [17] developed an UHPC with a compressive strength of 180 MPa, by considering the effect of w/b, type, and replacement proportion of filler.

The curing condition of UHPC has a major impact on its compressive strength. However, the models above have not addressed this effect. Ghafari et al. [18, 19] recommended several models for predicting the performance of UHPC under different curing conditions. This model can predict the compressive strength and the slump flow with higher accuracy, due to its distributed and nonlinear nature. Based on this model, the optimum amount for cement and silica fume was found to be at 24% and 9% by volume of concrete respectively [19].

7. UHPC MIXTURE PROPORTION IN COMMERCIAL USE:

The key factor in producing UHPC is to improve the micro and macro properties of its mixture ingredients in order to ensure mechanical homogeneity, maximum particle packing density and minimum size of flaws [20, 21]. The selection of UHPC compositions should not focus only the relative proportions of different grain sizes, but also on the appropriate selection of materials with proper physical and chemical properties. Some commercially available UHPC mixtures are given in Table 2 for guidance. It can be observed that high volume of cement content, SF, and sand are normally used in UHPC. The initial cost of UHPC far exceeds the commercial concrete.

Table 2.
Composition of Commercial UHPC

Materials (kg/m^3)	Mix-1	Mix-2	Mix-3	Mix-4
Portland cement	1114	1050	712	911
Fine sand (150 to 650 micron)	1072	514	1020	911
Silica fume (SF)	169	268	231	225
Ground Quartz	-	-	211	-
Accelerator	-	-	30	-
Steel fibers	234	858	156	173
SP	40	44	30.7	38
Total water	211	180	109	200

8. UHPC STANDARDS:

In mid-2016, two French national standards for UHPC known as NF P18-470 and NF P18-710 were published to provide technical guidelines for designing UHPC. In addition to these standards some more guidelines are available, that can be referred.

1. French Interim Recommendations [22]
2. German Recommendations [23]
3. Japanese Recommendations [24]

All these guidelines do not have “official” status. The availability of new standards allows clear and codified specifications, which are helpful of acceptance of UHPC for its use. The standardization process of UHPC in France was started in December 2012. Complying with these standards will help in achieving quality UHPC and promote widened acceptability. Similar types of standardization are also being developed in other countries such as Switzerland, China, Canada, and Japan.

9. APPLICATIONS OF UHPC:

The applications of UHPC are increasing. From the year 2000s, several countries have engaged in various applications of UHPC. In France, a lot of structures such as bridges, facades and slabs have been built with UHPC. In US, UHPC is widely used for maintenance and development of highway and other infrastructural works. The use of UHPC has increased in Germany. Italy, Malaysia, South Korea, Japan, and many other countries.

The excellent performance of UHPC offers new opportunities for infrastructure works, building constructions and many other important works. According to the recent market research, the global market size of UHPC was estimated 2016 at US$ 892 million in 2016 and this number is expected to grow by 8.6% in every year to US$ 1867.3 million in 2025 [25]. UHPC has become a worldwide attention with its commercial availability in many countries. Within the last two decades, extensive research projects had been conducted by the academics and engineers around the world in order to industrialize UHPC technology as the future sustainable construction material. Nearly 200 bridges have been completed by using UHPC in different countries. Other applications of UHPC can be seen in buildings, structural strengthening, retrofitting, precast elements and some special applications. Some important projects completed with UHPC are given in Table 3.

Table 3.
Some Completed UHPC Projects Worldwide

Sl. No.	Location	Type of Structure	Year	Remarks
1	Sherbrooke, Canada	Pedestrian bridge	1997	First UHPC structure
2	Seonyu, Seoul, South Korea	Footbridge	2004	Arch bridge with reduced segments
3	Bourg-les-Valence, France	Road bridge	2005	• 90 % reduction in steel reinforcement • 66 % weight reduction than normal CC
4	Mars Hill Bridge, USA	Road bridge	2006	• 1st UHPC highway bridge in USA • No shear reinforcement
5	Louis Vuitton Foundation, France	Cladding panels	2014	Innovative design
6	MUCEM, Marseille, France	Column & Façade	2003	• Unique design • Y-shaped column • 'Transparent' façade
7	Shawnessy LRT Station, Canada	Roof	2004	• Light weight • Little maintenance
8	Jean Bouin Stadium, Paris	Roof & Facade	2013	• Precast UHPC elements • Waterproof roof and facade • Slender structure with unique design

Louis Vuitton Foundation Cladding panels in France

MUCEM, Marseille, Column & Facade in France

Shawnessy LRT Station, Roof in Canada

Jean Bouin Stadium Roof & Facade in Paris

The chloride-induced corrosion has always been the major threat to reinforced concrete structures especially in marine areas. The high durability and resistance to chloride of UHPC makes it an ideal material for use in severely exposed environment. Use of UHPC in marine structures is one of the solutions to prevent corrosion of the reinforcement and very promising result have been reported of its use in such environments. UHPC has the potential for construction, overlays, repairing and strengthening of marine structures, such as piers and oil platforms. Besides chlorides, UHPC also has great resistance to most chemical and physical attacks. This gives the possibilities of using UHPC in more severe environmental conditions.

The ductile behaviour of UHPC makes it possible to be used for buildings and structures in seismic regions. The excellent workability enables UHPC to be cast into any shapes. Hence, UHPC blocks with different shapes could be an excellent material for precast. Since UHPC shows very good application prospects, more and more UHPC applications will be seen in the near future.

Bourg-les-Valence Road Bridge in France

Mars Hill Bridge Road Bridge in USA

Recently a beginning has been made in India by M/s. UHPC India Pvt Ltd to produce UHPC on commercial scale in Mumbai. The use of UHPC made in some structure in Mumbai [26].

GCC Clubhouse – UHPC Beams, Mira Road, Mumbai

Residential Bungalow" project at Tirupati, Andhra Pradesh

10. CHALLENGES:

In the last two decades, UHPC has been used for both structural and non-structural components in many countries. However, it has not yet become a mainstream technology for everyday use due to its high initial costs and the lack of design codes, thus restricting its application.

The lack of design codes, limited knowledge on both the material and the production technology and high cost limit the application of this outstanding constructing material. Successful achievement of the application of UHPC can be seen throughout the world, however there are still barriers limiting its application. Ongoing research and efforts are filling up knowledge gaps in order to commence use of innovative, affordable, sustainable, feasible and economical UHPC in the future. To date, there are several types of UHPC that have been developed in different countries and by different manufacturers. Compact Reinforced Composite (CRC), Multi-scale Cement Composite (MSCC) and Reactive Powder Concrete (RPC). In Malaysia, UHPC started its industrial-commercial penetration in late 2010 under the name Dura.

Another issue concerning the cost is the life cycle cost of UHPC structures. Structures made with UHPC will have much longer service life with lower maintenance and repair cost compared to normal concrete. However, the applications of UHPC is based on empirical skills and knowledge on the design and construction and these skills are not easily shared. The dissemination of information is extremely important to encourage its applications. The design and construction methods for the UHPC structures are different from the traditional provisions for conventional reinforced concrete.

The number of skilled architect, engineers and experts in UHPC design and construction is still limited. The producers of UHPC on regular basis are also very limited.

11. CONCLUSIONS:

UHPC is a very versatile new material having outstanding properties with extraordinary strengths and excellent durability achieved through homogeneity and packing density improvements. Since its introduction in mid 1990s, a great deal of knowledge on the materials, design and construction have been gained with UHPC use in different countries. Technical guidelines have been published in France, Japan, Germany and Switzerland. Two French national standards have also been published in 2016 to replace the guidelines and the professional recommendations. These Standards provide clear codified specifications, which is expected to further help in acceptance of UHPC at the international level.

Some applications of UHPC in Europe, North America and Asia have shown proven benefits on the service life and maintainability. In Malaysia, over last 10 years nearly 90 bridges have been constructed while another 20 at various stages of planning, design and construction. Successful applications of UHPC in variety of structures has been reported throughout the world.

Initial high cost, lack of design codes, limited available resources and skilled, manpower have limited its commercial development and application in construction industry. To make use of full potential of UHPC, co-operation between academics, owners, users, governmental bodies and industry is required. The knowledge and practical experience on UHPC should be freely shared by different stakeholders at national and international levels.

In India recently a modest beginning has been made of UHPC use in building elements, precast items for façade and other applications. It is hoped that notice of UHPC will be soon taken by BIS and code will be framed on its production, design and construction. UHPC is likely to gain wide acceptance in India due to its excellent properties and performance in service life in the coming decades.

ACKNOWLEDGEMENT:

1. RMCMA is highly thankful to Dr. Satish Jain of M/s. UHPC India Pvt Ltd for providing great help in preparation of this bulletin.
2. RMCMA also thankfully acknowledges the help taken from the "Report on Ultra-high performance concrete: From fundamental to applications". ScienceDirect – Volume 9, December 2018.

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26. Photos provided by kind courtesy of M/s. UHPC India Pvt Ltd, Mumbai.

ABOUT RMCMA

The Ready Mixed Concrete Manufacturer's Association (RMCMA), India is a non-profit industry organisation of leading Ready Mixed Concrete Producers from India, established in March 2002. The vision of RMCMA is to make Ready-Mixed Concrete the preferred building material of choice for construction as the best environment-friendly sustainable material. The RMCMA is committed to provide leadership to the Ready Mixed Concrete industry in India. It promotes the interests of the entire Ready Mixed Concrete industry in India, without sacrificing the interests of end users, designers, specifiers, owners and other stakeholders. RMCMA strongly supports the Quality Scheme for RMC Plants as spearheaded by Quality Council of India (QCI) and BIS. RMCMA through its efforts have already brought about 350 RMC plants throughout the country under certification scheme. RMCMA is endeavouring that all RMC plants in India shall be brought under the umbrella of 3rd party certification. RMCMA is focused on following activities.

1) Organising Training Programs for different officials working in RMC Industry. RMCMA is conducting on regular basis following training programs.
   a) Concrete Technologist of India (CTI) for QC and Technical support service staff of Cement and Concrete industries.
   b) RMC business overall view for Marketing and New QC staff.
   c) Safety, Hygiene and Environment Training Program in association with National Safety Council of India for safety in RMC operations.

2) Creating awareness about advantage of quality concrete in construction.

3) Certification of RMC Plants through QCI and BIS.

4) Participation at National and International level to promote RMC.

5) Participating in formulation and revision of Codes with BIS pertaining to concrete and RMC.

6) Safety, Health and Environment requirements at RMC Plants.

7) Dissemination of Knowledge amongst Civil Engineers and QC Professionals on Concrete Technology through publishing Bulletins and holding Round Table Conferences.

8) Participation in Seminars/ Conferences and Exhibitions for promotion of RMC.

9) Focusing on use of Special Concretes or niche applications.

10) Organizing lectures in engineering colleges to expose students on RMC Technology.

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