Use of Galvanized Steel Reinforcements in Concrete Structures

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Corrosion in Hong Kong

- In Hong Kong, there is little scientific guideline or design recommendation on corrosion protection of civil engineering and building structures specifically developed under local environmental conditions.

- In general, many structures are considered to perform satisfactorily so far. However, their service lives have not been checked.

  Assuming a service life of 50 years is readily achieved with current design and construction practice, how to increase the design service live to 120 years ? What should be done accordingly ?

- Corrosion protection engineering is an emerging discipline which may be able to answer some questions.

Corrosion Protection in Hong Kong

- An effective design model for atmospheric corrosion for civil engineering and building structures in Hong Kong, Macau and the Pearl River Delta Region under local environmental conditions.

- Effective means of corrosion protection in-line with current constructional practice to enhance the corrosion resistances of structures.

- Specifications for corrosion protection using hot-dip galvanization together with complementary testing, inspection and quality assurance procedures.

Overview

- Two industry-led research and development projects on effective corrosion protection to structural steel members using hot-dip galvanization were undertaken at the PolyU from May 2010 to April 2012, and then May 2012 to October 2013.

- One of the key objectives of the project is to develop an innovative galvanization process using Zinc-Aluminum alloys together with a complementary surface pre-treatment. The process is derived from the well established "Galfan" (*www.galfan.com*) which had been specifically developed and applied in the form of "continuous galvanization" for steel strips and wires.

- During the course of these two ITF projects, the continuous process is modified into a "discrete" process successfully, and galvanization layers with enhanced mechanical properties and corrosion resistances have been produced repeatedly on samples of steel plates and steel reinforcements.

ITF Platform Project
Project Reference: ITP/032/09NP

Project title: *Enhanced ductility and service life of galvanized structural steel members*

Project coordinator: Professor K F Chung, PolyU

Deputy project coordinator: Dr C Zhang, NAMI, ITC

Project sum: HK$4,977,000 (10% from industry)

Project duration: 1 May 2010 to 30 April 2012

Industrial collaborators: Yau Sang Galvanizer (Hot-Dip) Co. Ltd.
Wo Lee Steel Co. Ltd.

ITF University Industry Collaborative Project

Project Reference: UIM/217

Project title: *Enhanced durability and mechanical performance of structural steel members using an innovative galvanization process*

Project coordinator: Professor K F Chung, PolyU

Deputy project coordinator: Dr L L Yeung, HKUST

Project sum: HK$1,690,000 (50% from industry)

Project duration: 1 May 2012 to 31 October 2013

Industrial collaborator: Yau Sang Galvanizer (Hot-Dip) Co. Ltd.

Scope

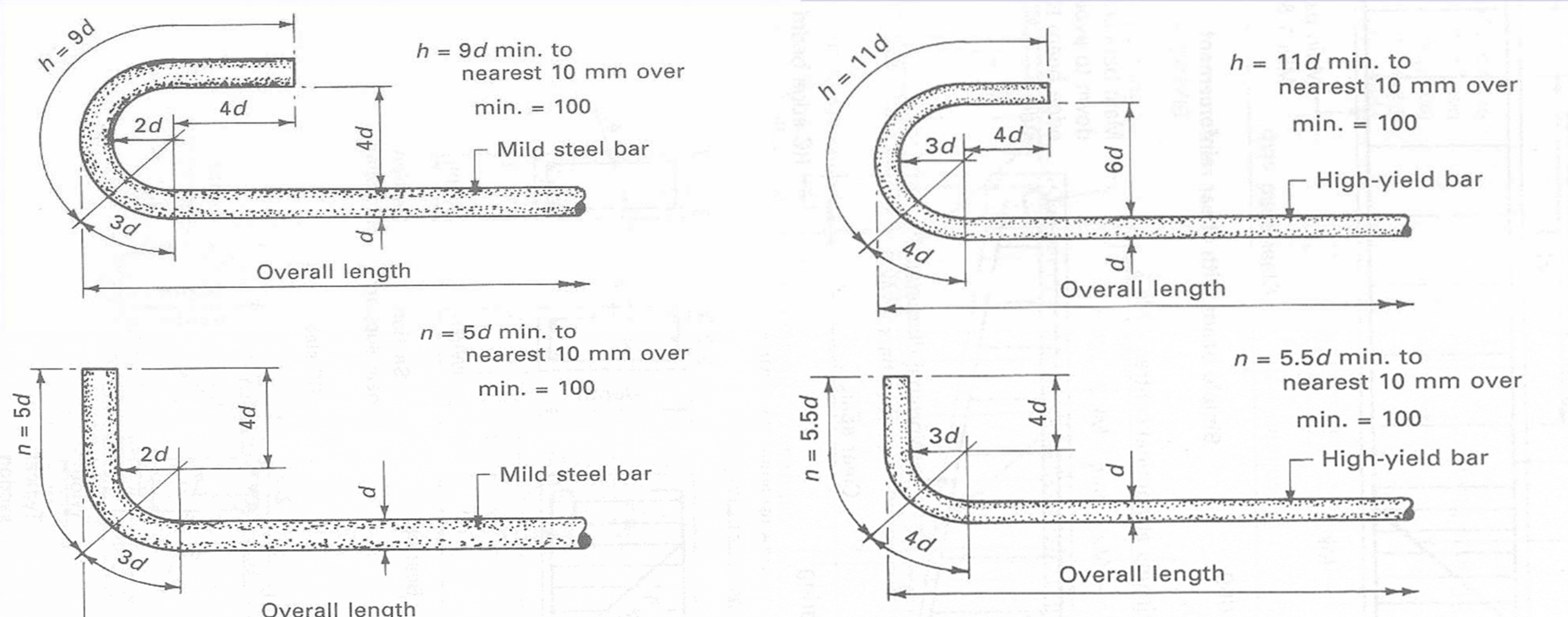
This lecture presents some of the key findings of the ITF projects on innovative galvanization using Zinc-Aluminum alloys:

- Chemical compositions and micro-structures of galvanized coatings
- Improved corrosion resistances of galvanized coatings in accelerated corrosion tests
- Permissible internal bent radii of galvanized rebars
- Thicknesses of galvanized coatings obtained with direct and indirect measurements
- Bond strengths of concrete embedded galvanized rebars in pull-out tests

One of the key objectives is to produce galvanized steel rebars with galvanization coatings of high ductility so that these steel rebars are bent after galvanization.

Typical application in reinforced concrete structures

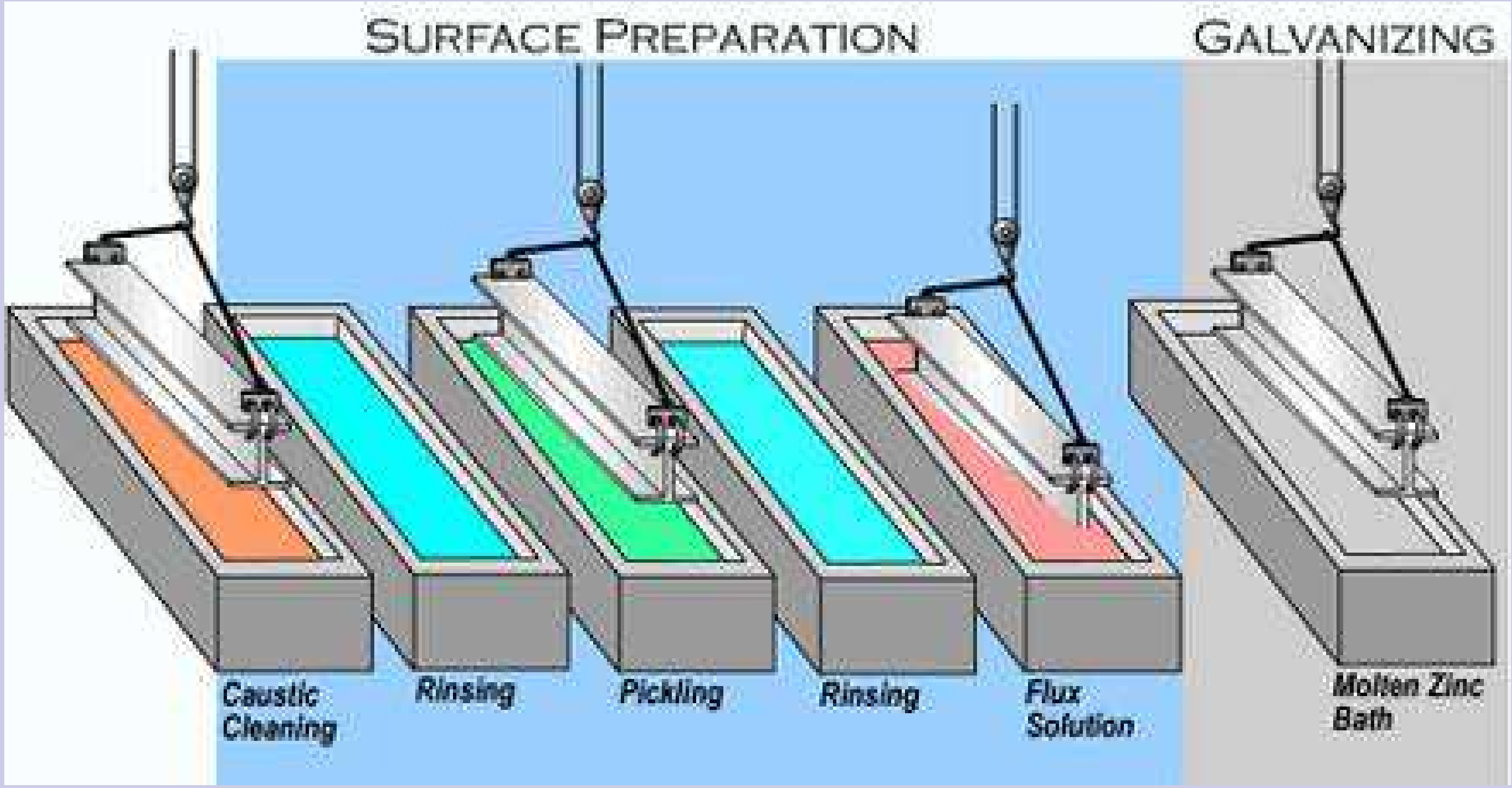
Bending schedule of steel rebars



Standard hooks and bends

Hot-dip galvanization

- Hot-dip galvanization has grown almost continuously since it was first used to protect corrugated iron sheets 150 years ago.
- Its ability to grow in the face of sophisticated competition is the result of the simplicity of the process and the unique advantages of the coatings.



Corrosion protection using hot dip galvanization

- In general, the level of corrosion protection provided in hot-dip galvanized steel members depends on:

  - the chemical composition of galvanization coatings, which is directly related to the zinc concentration of the molten zinc bath, and

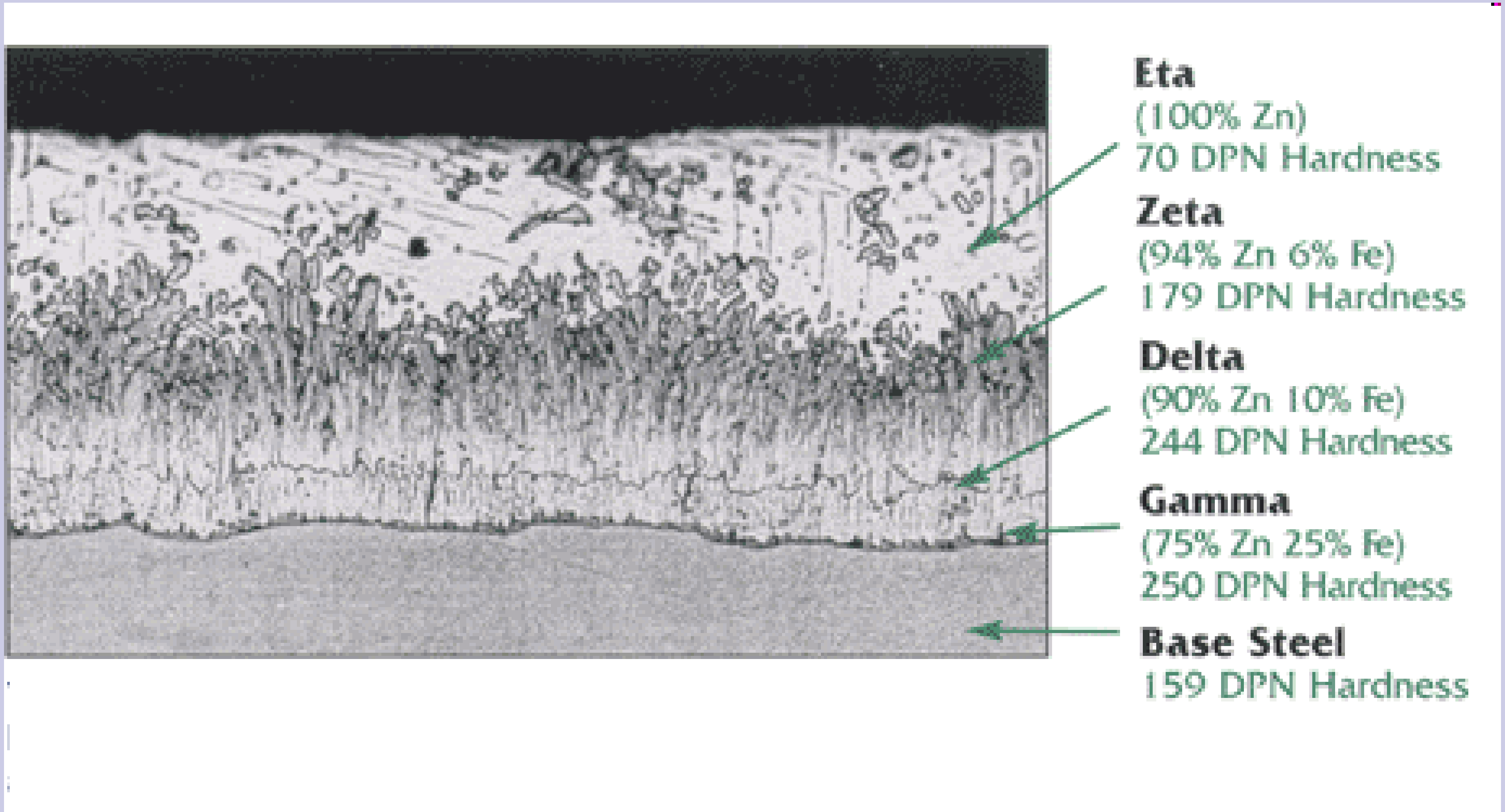
  - the thicknesses of galvanization coatings, and their variations throughout the entire surfaces of the steel members.

- While the zinc concentration of the molten zinc bath may be readily controlled through regular monitoring of the *chemistry* of the zinc bath, consistency in the coating thicknesses should be established using *a number of well controlled operations and procedures* which are to be performed by *an experienced operator* in a galvanizer.

Conventional galvanization

Micro-structure of Zn alloys

A photomicrograph of a galvanization coating shows three Fe-Zn alloy layers and a layer of pure metallic zinc.



Innovative galvanization using Zn-Al alloys

- The Galfan technique using Zn-Al alloys with at least 5% Aluminum is widely used to produce galvanized steel wires and strips in a continuous process.

- It is proposed to modify the process to produce galvanized steel members in a discrete process, i.e. hot-dipping.

- Similar to the conventional galvanization process, it is necessary to provide good surface condition of the steel members, and a complementary surface pre-treatment should be carefully conducted. This includes caustic cleansing, pickling as well as fluxing.

- A complementary galvanization procedure should be established: temperature of molten zinc bath, immersion rate, dipping time, withdrawal rate, and any post-treatment, if necessary.

- Moreover, it is essential to remove galvanization by-products, in particular, Aluminum oxides which should be removed from the surfaces of the steel members once they are formed.

Innovative galvanization using Zn-Al alloys

Yau Sang Galvanizers (Hot-Dip), Yuen Long
September 2013

Innovative galvanization using Zn-Al alloys

Steel plates – 6 mm S235
8 mm S275
10 mm S355

Steel rebars – Y10 S460
Y20 S460

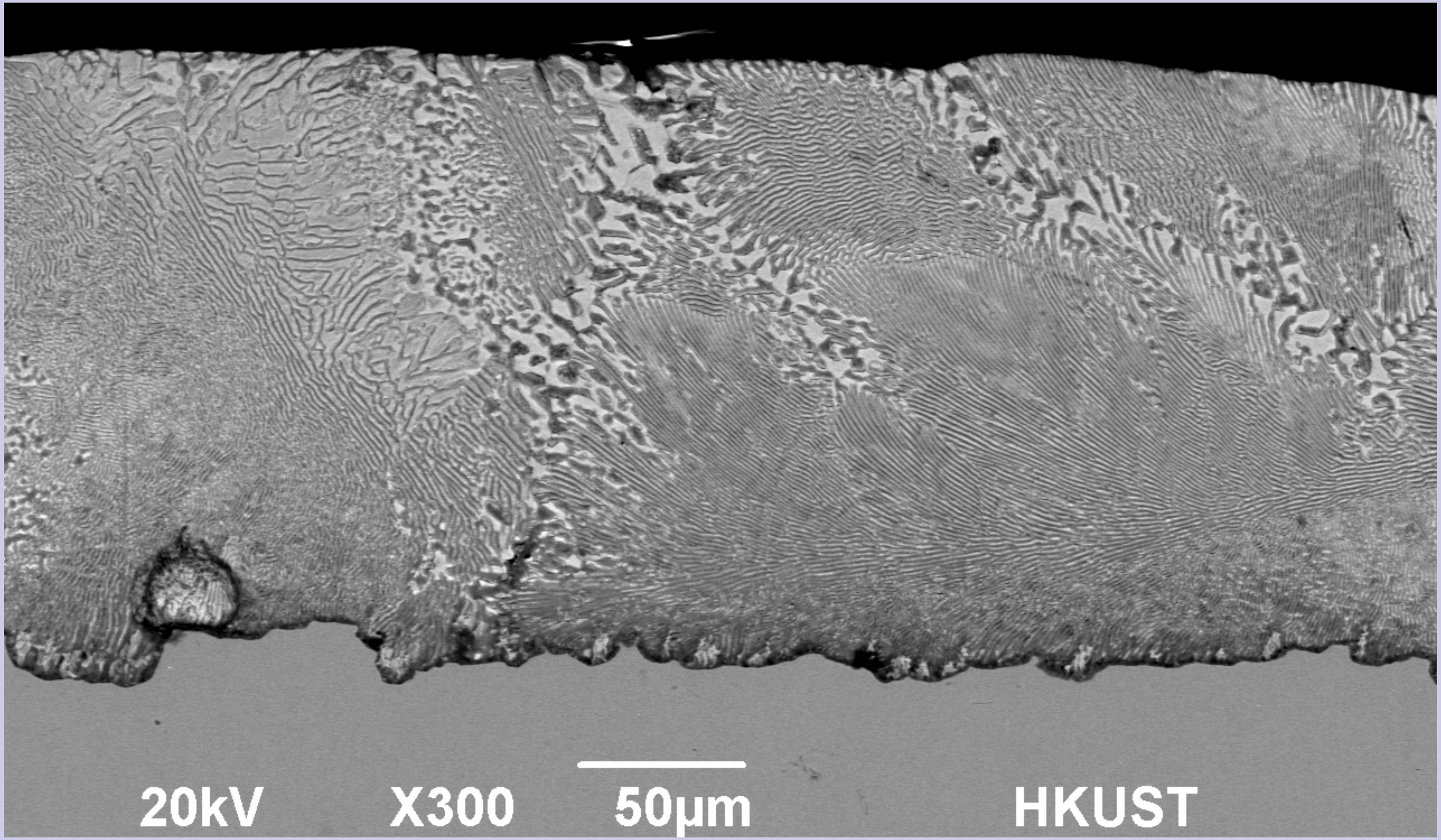
Ultra-high Resolution Scanning Electron Microscope

Material Characterization and Preparation Facility

The Hong Kong University of Science and Technology

Innovative galvanization using Zn-Al alloys

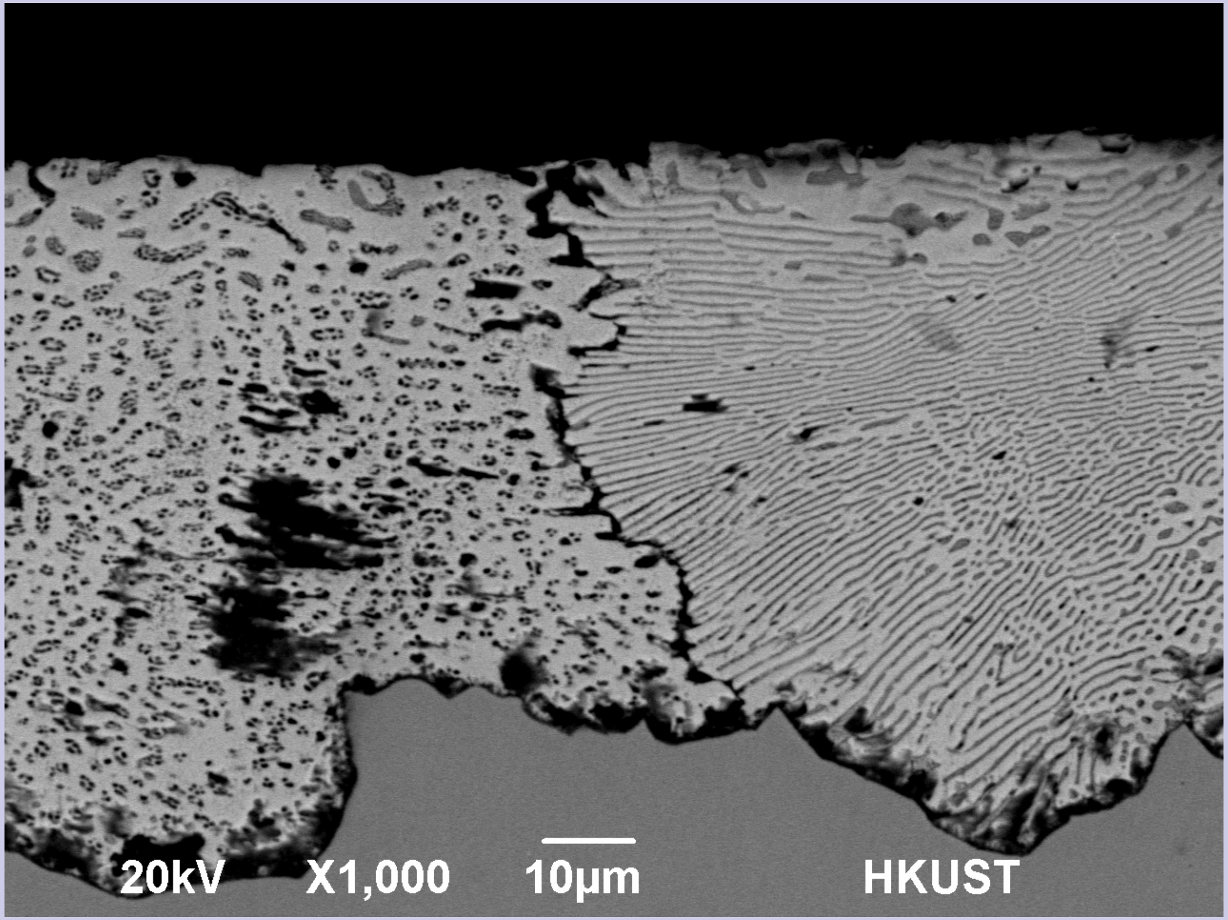
Micro-structures of Zn-Al alloys



Scanning Electron Microscopy / Energy-Dispersive X-ray spectroscopy
Materials Characterisation and Preparation Facility, HKUST
11 October 2013

Innovative galvanization using Zn-Al alloys

Micro-structures of Zn-Al alloys



Scanning Electron Microscopy / Energy-Dispersive X-ray spectroscopy
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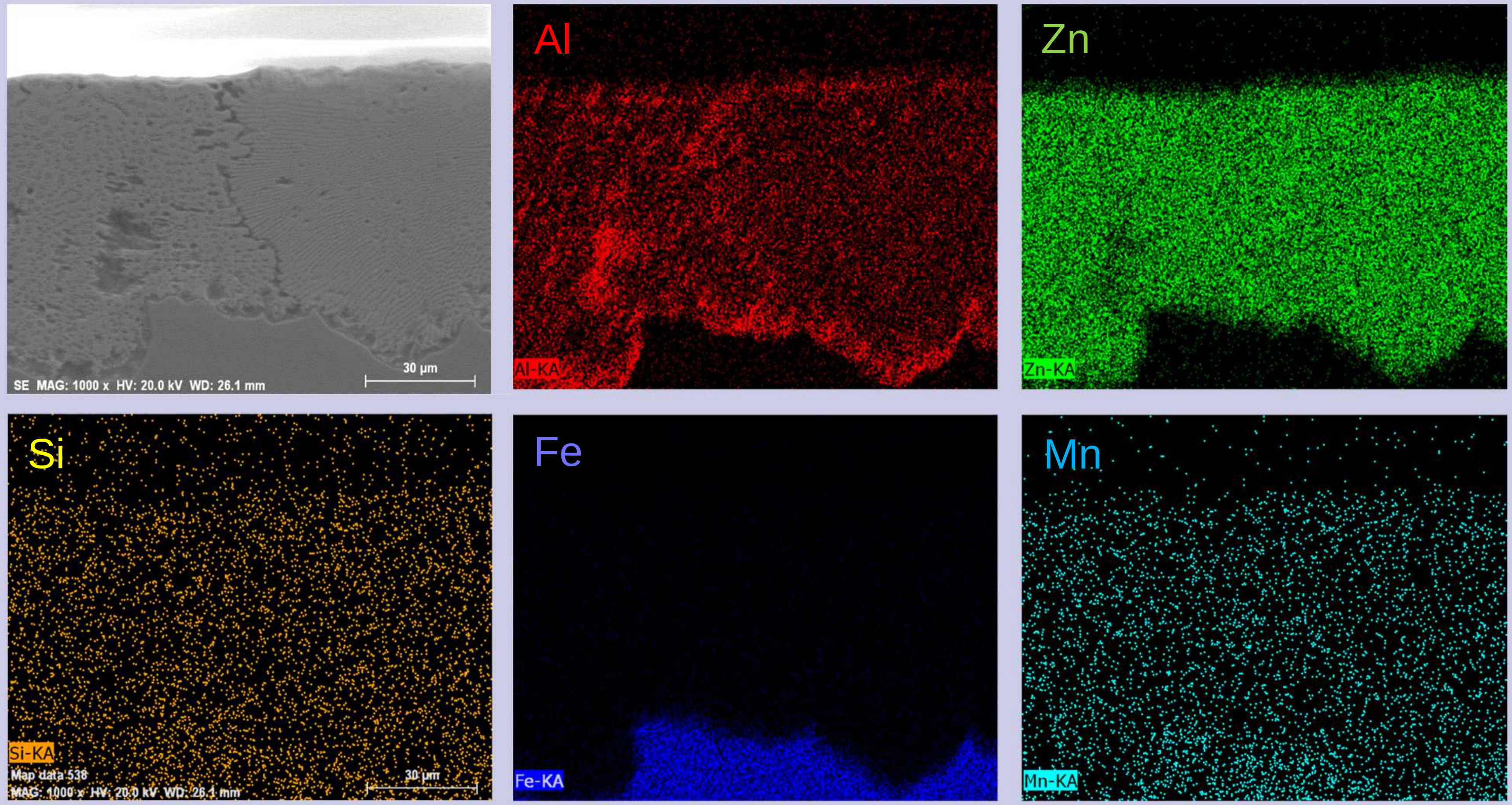
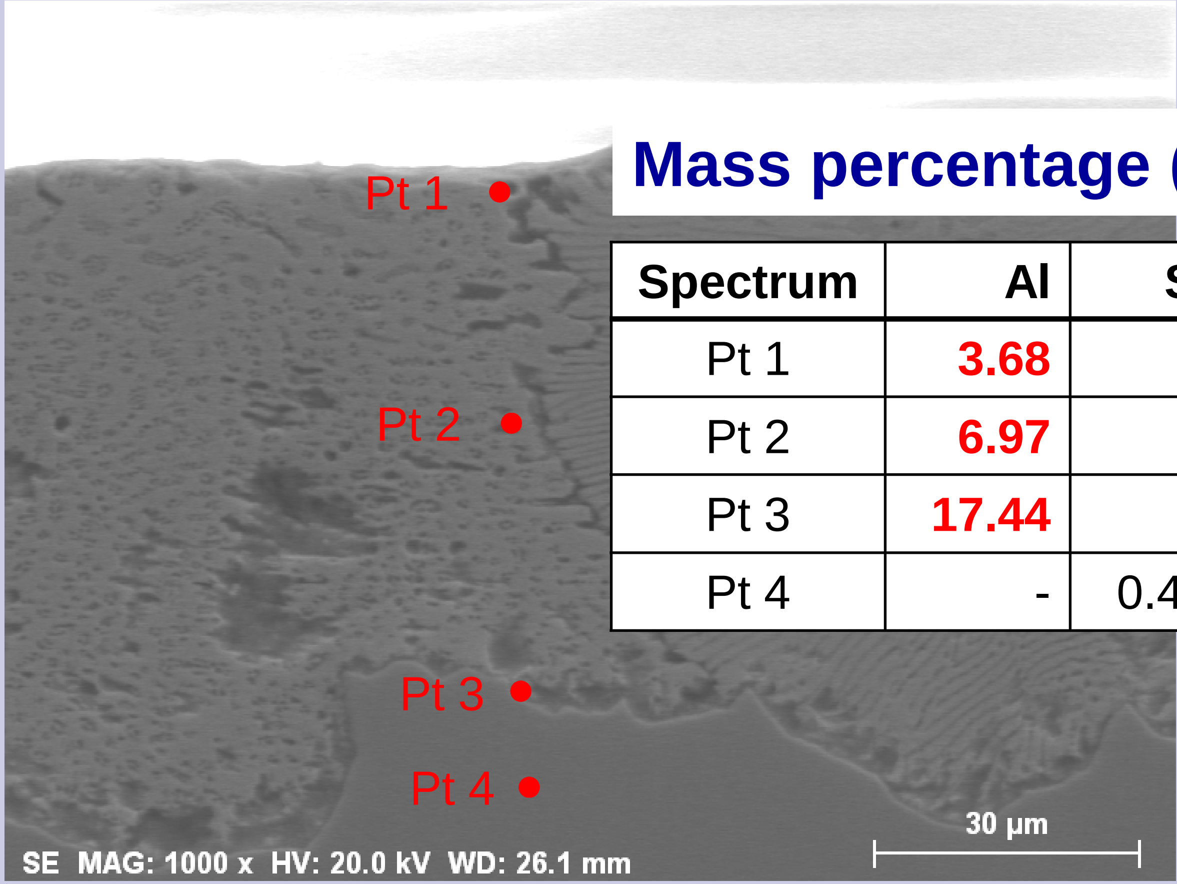
Chemical compositions of galvanization coatings



SEM/EDX analysis on galvanization coatings of Zn-Al alloys



Mass percentage (%)

Spectrum	Al	Si	Mn	Fe	Zn
Pt 1	**3.68**	-	-	-	96.32
Pt 2	**6.97**	-	-	-	93.03
Pt 3	**17.44**	-	-	2.64	79.93
Pt 4	-	0.42	2.07	97.51	-

Scanning Electron Microscopy / Energy-Dispersive X-ray spectroscopy
Materials Characterisation and Preparation Facility, HKUST
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Neutral salt spray tests to ASTM B117

NSS Test Chamber, Water Laboratory, PolyU

Neutral salt spray tests to ASTM B117

NSS Test Chamber, Water Laboratory, PolyU

Neutral salt spray tests on steel plates

Mass loss method after 192 hours of exposure: ASTM A90

Specimen	Steel Grade	Reduction in coating thickness (µm)	Average (µm)	Ratio
CGA01 CGA02 CGA03	S275	8.37 8.94 9.75	**9.02**	**0.28**
GGA01 **GGA02** **GGA03**	**S275**	**2.73** **2.19** **2.69**	**2.54**	
CGB01 CGB02 CGB03	S355	10.35 12.52 9.69	**10.85**	**0.25**
GGB01 **GGB02** **GGB03**	**S355**	**2.09** **2.92** **3.05**	**2.69**	
CGC01 CGC02 CGC03	Q235	8.19 9.29 10.22	**9.23**	**0.31**
GGC01 **GGC02** **GGC03**	**Q235**	**2.99** **2.71** **3.00**	**2.90**	

Permissible internal radii for bent bars

Hong Kong Concrete Code 2013

Bar diameter, d	Minimum internal bend radius for hooks and loops
≤ 12 mm	2 d
< 20 mm	3 d
≥ 20 mm	4 d

Rebar bending test results – Y20 rebar

Unbent rebar

Bent rebar

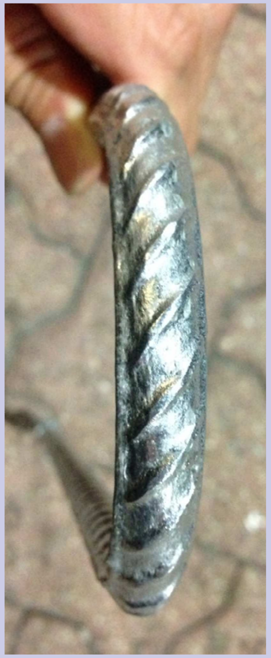
Bending radius = 3 d

Rebar bending test results

Y10 rebar	Y20 rebar

Y10 rebar

Unbent rebar



Bent rebar

Bending radius = 2 d

Y20 rebar

Unbent rebar

Bent rebar

Bending radius = 3 d

Current specification of galvanized rebars in Hong Kong

CEDD General Specification for Civil Engineering Works 2006 (2013):

15.06(1) "Hot dip galvanizing to reinforcement shall comply with BS EN ISO 1461:1999. The galvanization shall be applied after cutting and bending of the reinforcement. "

BS EN ISO 1461:1999 Hot dip galvanized coatings on fabricated iron and steel articles – Specifications and test methods.

Minimum coating thickness	Sampling points for magnetic method
For steel thickness ≥ 6 mm, • Overall mean ≥ 85 µm • Local mean ≥ 70 µm	• A minimum of 5 readings in each reference area. • A minimum of 3 reference areas for each article with a surface area ≥ 2 m^2.

How about galvanization coating with Zn-5%Al ?

Measurement of coating thicknesses

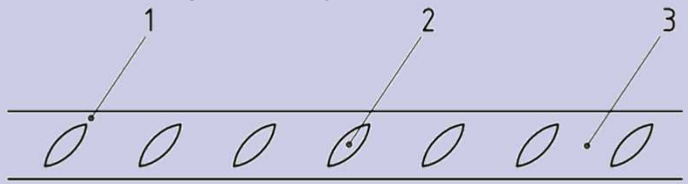
ISO 14657:2005 Zinc-coated steel for the reinforcement of concrete

Minimum coating thickness

Class A: 84 µm for d > 6 mm
69 µm for d ≤ 6 mm
Class B: 42 µm
Class C: 19 µm

Sampling points for magnetic method

- A minimum of 30 judiciously distributed measurements.
- Equal number of measurements at areas 1, 2 and 3, respectively.



ASTM A 767/A 767M-09 Standard specification for zinc-coated (galvanized) steel bars for concrete reinforcement

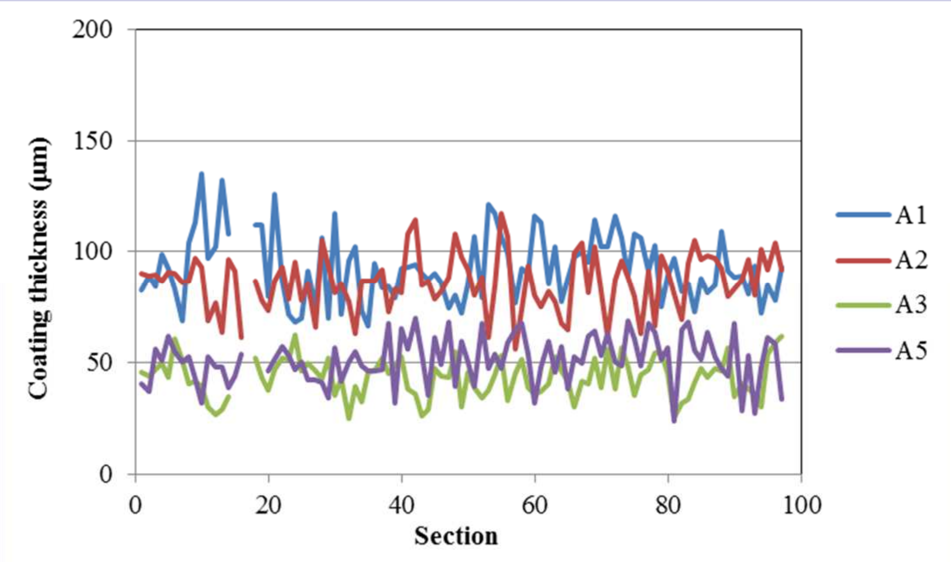
Minimum coating thickness	Sampling points for magnetic method
Class 1: 128 µm for d = 10 mm 150 µm for d ≥ 13 mm Class 2: 85 µm for d ≥ 10 mm	• At least five measurements shall be made in each of the three sampling areas.

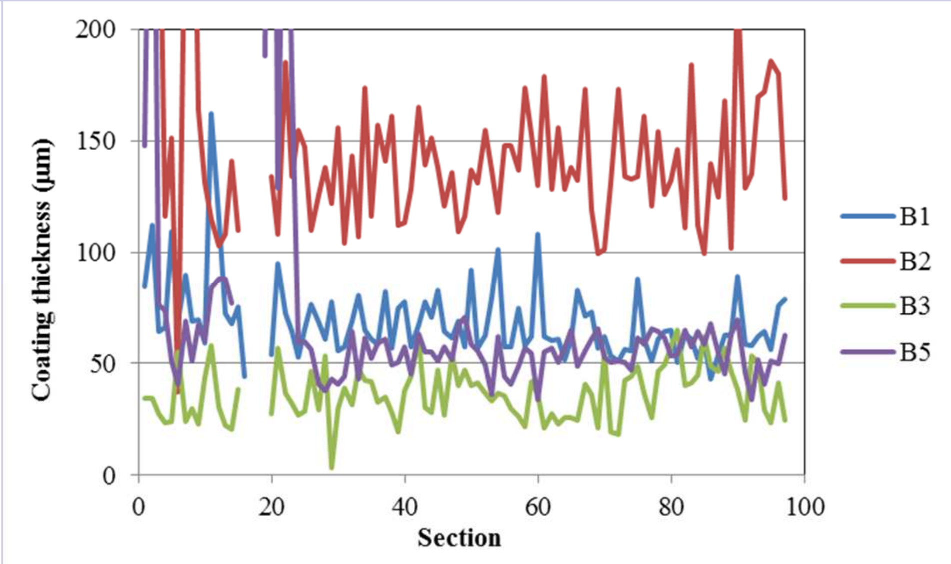
How about galvanization coating with Zn-5%Al ?

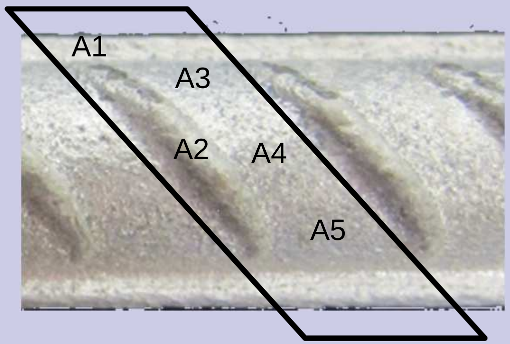
Measurement of coating thicknesses

Specimen	Dimension	Galvanization	Key Chemicals	Gravimetric Method	Mass Loss Method
R11	*Ø10 x 800 mm*	Conventional	Zn	✓	-
R12	*Ø20 x 800 mm*	Conventional	Zn	✓	-
R31	*Ø10 x 250 mm*	Innovative	Zn-5%Al with surfactant	✓	✓
R32	*Ø10 x 250 mm*	Innovative	Zn-5%Al with surfactant	✓	✓

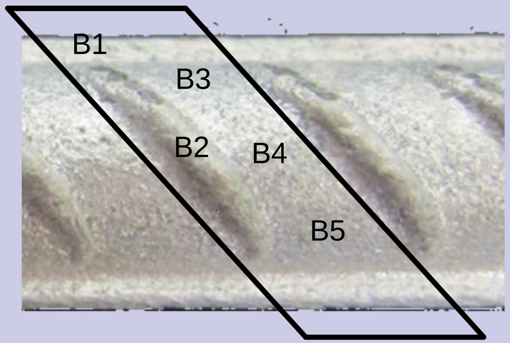
Measurement of coating thicknesses







Front side



Back side

Mass loss method to ASTM A90

Specimen	Length (mm)	Diameter (mm)	Rebar surface area (mm^2)	Mass loss (g)	Thickness reduction (μm)
R31	109	10	3419	2.82	124.5
R32	115	10	3624	2.71	120.3

Measurement of coating thicknesses

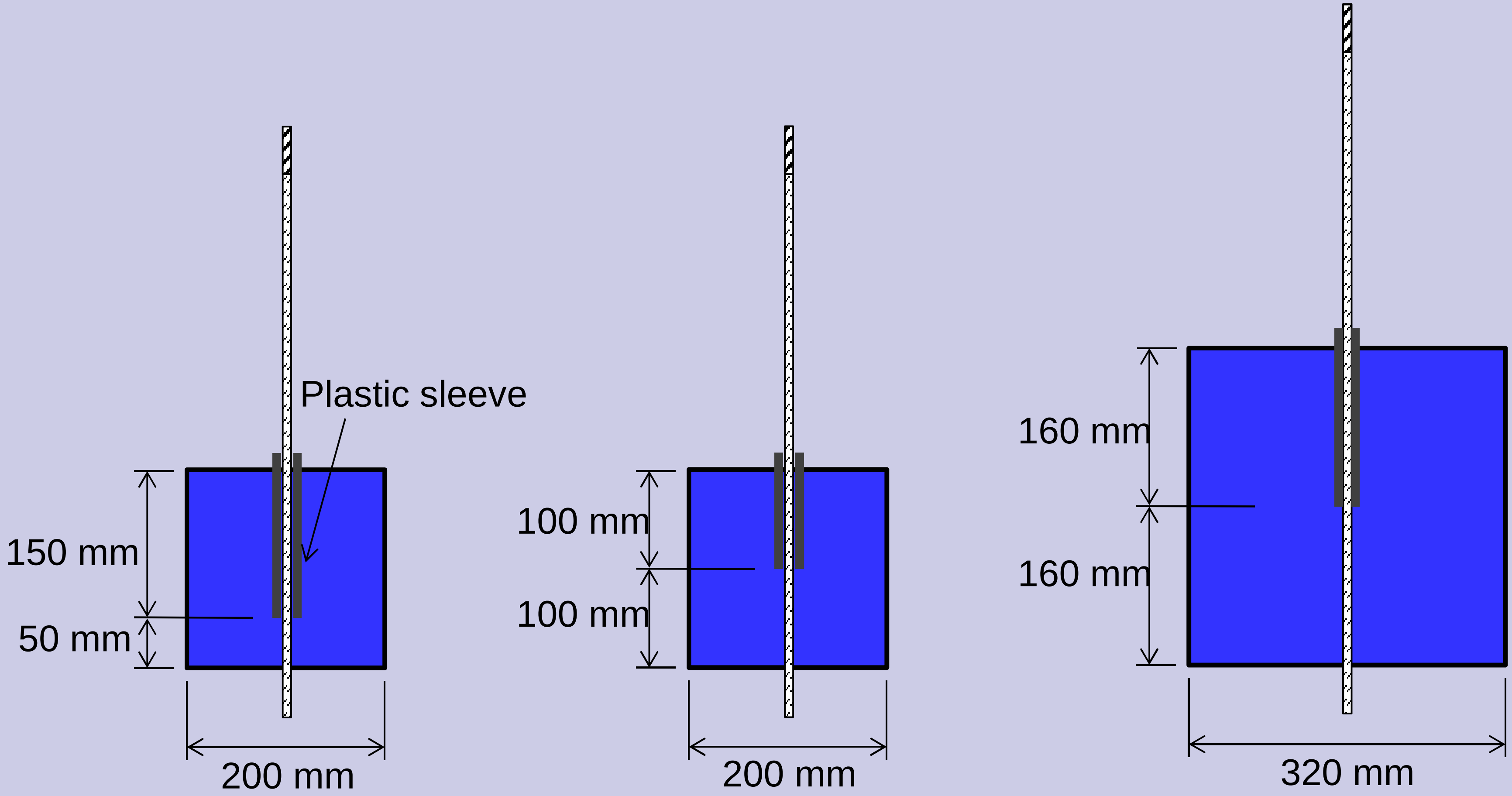
Summary

Specimen	Galvanization pprocess	Key chemicals	Dimension (mm)	Coating thickness by gravimetric method (mm)	Coating thickness by mass loss method (mm)
R11	Conventional	Zn	Ø10 x 800	**148.3**	**-**
R12	Conventional	Zn	Ø20 x 800	**185.4**	**-**
R31	Innovative	Zn-5%Al with surfactant	Ø10 x 250	**144.1**	**124.5**
R32	Innovative	Zn-5%Al with surfactant	Ø10 x 250	**126.6**	**120.3**

Bond strength tests on galvanized rebars

Apr 2013 – Sep 2013

Pull-out tests to BS EN 10080



Specimens with Y10 rebars

Specimens with Y20 rebars

Specimens with Y32 rebars

Bond strength tests on galvanized rebars

Pull-out tests to BS EN 10080

Test programme

C25 concrete	Y10		Y20		Y32		
Zn-5%Al	*A01-A03*	*A04-A06*	*B01-B03*	*B04-B06*	*C01-C02*	*C03-C04*	*C05-C06*
Zn	*A11-A13*	*A14-A16*	*B11-B13*	*B14-B16*	*C11-C12*	*C13-C14*	*C15-C16*
Black Steel	*A21-A23*	*A24-A26*	*B21-B23*	*B24-B26*	*C21-C22*	*C23-C24*	*C25-C26*
Cube size	200 × 200 × 200				320 × 320 × 320		

C50 concrete	Y10		Y20	
Zn-5%Al	*A101-A103*	*A104-A106*	*B101-B103*	*B104-B106*
Zn	*A201-A203*	*A204-A206*	*B201-B203*	*B204-B206*
Black Steel	*A301-A303*	*A304-A306*	*B301-B303*	*B304-B306*
Cube size	200 × 200 × 200			

Bond strength tests on galvanized rebars

Pull-out tests to BS EN 10080

Curing of concrete

Bond strength tests on galvanized rebars

Pull-out tests to BS EN 10080

Apr 2013 – Sep 2013

Bond strength tests on galvanized rebars

Pull-out tests to BS EN 10080: Typical failure modes

Bond failure
Y10, Y20 & Y32 rebars
embedded in
C25 concrete

Rebar fracture
Y10 & Y20 rebars
embedded in
C50 concrete

Bond strength tests on galvanized rebars

Pull-out tests to BS EN 10080

Type of rebars	Bond strength (N/mm^2)				
	Grade 25 concrete Measured f_{cu} = 19.4 N/mm^2			Grade 50 concrete Measured f_{cu} = 41.0 N/mm^2	
	Y10	Y20	Y32	Y10	Y20
Black steel	7.6	11.5	14.0	---	---
Galvanized rebars with Zn alloys	7.7	12.1	14.7	---	---
Galvanized rebars with Zn-Al alloys	8.3	10.6	14.6	---	---
Failure mode	Bond failure			Rebar fracture	

Design value, f_{bu}	2.2	3.2

Hong Kong Concrete Code 2013: Cl. 8.4.4
Design ultimate anchorage bond stress, $f_{bu} = 0.5\sqrt{f_{cu}}$ N/mm^2

Key findings

- Chemical composition
  At least 5% Al in the galvanization coatings.

- Corrosion resistance
  The corrosion rate of Zn-Al alloys is only 0.25 to 0.31 to that of Zn alloys.

- Internal bending radii
  2 to 3 d, where d is the diameter of the steel rebars

- Typical coating thicknesses
  120 to 145 μm although only 85 μm x 0.31 = 26.4 μm is needed.

- Bond strengths
  8.3 to 14.6 N/mm^2 when compared with the design value, f_{ub}, of 2.2 N/mm^2

In addition, a technical guideline is being compiled from design and construction engineers on the effective use of hot-dip galvanization for corrosion protection, including

i) the corrosion design model on atmospheric corrosivity in Hong Kong,
ii) the galvanization procedure using Zn-Al alloys, and
iii) the inspection and quality control procedures on measurements of the galvanization coatings.

Conclusions

- This lecture presents some of the key findings of two ITF projects on the effective use of hot-dip galvanization using Zn-Al alloys. Both the ductility and the corrosion resistances of the galvanization coatings are significantly enhanced.

- Both the projects aim to contribute to the science of corrosion protection to reinforced concrete structures. Galvanized steel rebars rarely rust, and their use will successfully eliminate local concrete spalling.

- The projects have generated important scientific data for possible development of a corrosion design model for infrastructures in Hong Kong.

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i) Yau Sang Galvanizers (Hot-Dip) Co., Ltd., and

ii) Wo Lee Steel Co., Ltd.

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