

Copper-clad aluminum as an alternative to copper flexible conductors for electric power cables: opportunities and challenges

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ABSTRACT

The majority of flexible conductors for LV power cables is today made with Copper. Use of alternative metals for these cables is investigated, under the push of significant cost reduction. Aluminum is an alternative but some technical concerns are considered in terms of mechanical and corrosion resistance properties. Bimetallic conductors like copper-clad aluminium can combine advantages of the 2 metals, with attractive cost. LV flexible cables were produced with Cu, CCA, tinned CCA and Al class 5 conductors; CCA conductors were evaluated in terms of quality and integrity of copper layer; an evaluation of main cable properties was considered.

KEYWORDS

Cu, CCA, copper-clad aluminium, aluminum, flexible conductors, class 5 conductors, LV cables.

INTRODUCTION

The pressure of high copper prices during the last decade requires innovative solutions to reduce its strong impact on material costs for wire and cable (W&C). Aluminum is a well-known material for producing conductors with a good cost/performance ratio (conductive and lightweight) that has been used for many years. Nowadays, copper is still largely used in W&C and its replacement with aluminum presents challenges for various reasons: a larger diameter of aluminum is required to match the resistance of a copper conductor, aluminum's mechanical properties (tensile strength) are inferior to those of copper, aluminum presents processing difficulty in fine wires (i.e. drawing to <0.5mm diameter), and aluminum offers poor corrosion resistance.

Bimetallic conductors like copper-clad aluminum (CCA) offer interesting key features for niches of cables where aluminum is not a viable choice versus copper. Several grades of bimetallic conductors are available on the market, but not all of them are adequate for applications in the electric cable industry. In this sense, the manufacturing technology can seriously affect quality: cladding is strongly preferable to electroplating.

The objective of this work is to evaluate metals like aluminum, CCA and tinned CCA as alternatives to copper for flexible conductors in building wires and LV power cables. Cables have been designed with conductors having the same DC resistance. Prototype cables were manufactured and characterized according to the

specifications required for copper cables used in the application. Additional tests were carried out to simulate aggressive environmental conditions with heating thermal cycles.

Special focus is given to the definition of high-quality CCA and its related characteristics. Special tests are described in order to select material with resistance to corrosion similar to that of copper.

High-quality CCA conductors, as produced according to Copperweld technology (Copperlite™ CCA) in combination with the use of selected raw materials, show process characteristics close to those of copper, especially when it is drawn to fine diameters (i.e. multi-wire 8x0.25mm) as required for flexible cables. The strong metallurgical bond between the aluminum and copper obtained with Copperlite™ CCA enables the drawing of fine wires (i.e. down to 0.20 mm diameter at 20m/sec production speed, in conventional copper drawing equipment) with no impact on the Al/Cu volume ratio and maintains a strong bond at the interface between the two metals

Prototype cables manufactured with high-quality CCA conductors showed performance comparable to that of copper, even in severe high-humidity conditions, whereas aluminum conductor cables failed.

ALTERNATIVE METALS TO SUBSTITUTE COPPER AS FLEXIBLE CONDUCTORS FOR LV CABLES : AL AND CCA

Copper has been predominantly used in power cable applications as it provides the best conductivity for the best price as compared to silver or gold. Increasing copper price and copper theft lead to the search for a cost saving and theft deterrent product. Aluminum has been investigated and used in LV and MV power cable applications as a cost saving alternative. Cables such as building wire, service drop, parallel aerial cable, secondary UD cable, and 600 V power cables can be manufactured using aluminum and are available commercially in the US market. Even though aluminum has been widely used in US market, there are still significant concerns in special applications due to its oxidation and creep phenomena. Two people died in a house fire due to an overheated aluminum wire connection at a wall receptacle [1].

Another alternative is Copper Clad Aluminum (CCA). CCA provides advantages in light weight and cost savings similar to aluminum wire without the bad stigma and concern in connectivity/termination. CCA provides good connectivity at termination, which is comparable to copper due to the copper clad surface of CCA [2]. Some applications in which CCA can certainly be more beneficial to use, as compared to aluminum, are street lighting applications and telecommunication cables.

MAIN FEATURES OF HIGH QUALITY CCA AND TINNED CCA

Copperlite™ CCA, Key performance characteristics

- Light weight
 - Copperlite™ shows higher flexibility and lighter weight in comparison with copper,
 - Comparing wires of the same size, the weight of a copper conductor is approximately 2.7 times higher than Copperlite™,
 - Comparing wires with same conductivity, Copper's weight is approximately twice that of Copperlite™;
- Skin effect
 - High-frequency AC current density is greater near the outside surface of the wire than at its center; Copperlite™ is widely used for HF TLC cable;
- Anti-theft
 - The valuable copper content in the conductor cannot easily be recovered using common metal reprocessing techniques and can only be sold as mixed scrap metal, generating far less value for thieves;
- Recycling
 - Industrial Copperlite™ scraps can be recovered in a very special aluminum alloy where small amount of copper is required, Dynext will provide this high added-value service to its customers;
- Environmentally friendly
 - Compared to electrochemical process, metallurgic bonding is an environmentally friendly process with low energy consumption; Copperlite™ will bring an improvement in Carbon dioxide emission to a final product.

Tinned CCA offers additional advantage particularly in high stressed corrosion environment as for high humidity and presence of aggressive chemicals, i.e. sulfur agent typically of Oil & Gas cable application.

Cable design: Copperlite™ vs Copper, main advantage

MATERIAL	DIAMETER	AREA	WEIGHT	RESISTANCE	WEIGHT SAVINGS vs Copper
	mm	mm ²	kg/km	Ω/km	%
Copper	1,129	1,00	8.94	17,149	0
CCA 10%	1,428	1,60	5.31	17,149	40

Copper wire replacement with CCA10% same Resistance requires:

- ✓ 60% higher cross-section
- ✓ 26% higher diameter
- ✓ 40% weight savings

Main current applications

- Telecommunication (TLC) cables
 - CATV, Coaxial, Data, High Frequency
 - To avoid theft trouble, a new Twisted pair aerial TLC cable in CCA has been already introduced and is being currently used by Telecom Italia according to its Spec. CT 948, Sept 2011,

The new cable are installed from more than one year in the Telecom Italia network with no more theft troubles

- LV Power Cable
 - Low Voltage multi-polar cable, concentric neutral conductor in CCA alternative to Copper, ENEL Spec. DC 4126, Aug 2010
- MV power cable as for screen wire

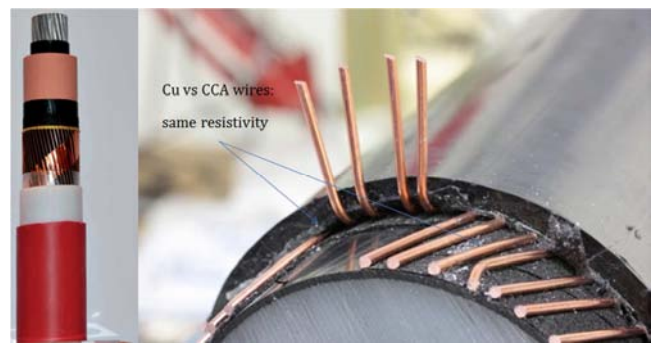


Figure 1 : Medium Voltage power cable having screen wire.

- Screen wire of MV power cable in Copper can be replaced with Copperlite™ CCA designed with the same conductivity, offering the same cable performance
- Ageing test under typical underground condition of MV power cable (i.e. 100% of relative humidity, 60°C) showed performance of Copperlite™ CCA very similar to Copper wires against Aluminum wire, where just after a short period of ageing time, showed pitting corrosion phenomenon with a significant increase of surface resistivity of the single wire

CCA conductor drawing

Flexible Cable conductors, general aspects.

This application requires flexible conductor design in single end very fine wires. Typically, class 5 according to IEC 60228 standard requires single end sizes 0.50mm, 0.41mm and 0.21mm according to the different final cross-section design.

Cross-section (mm ²)	Single end diameter (mm)
0,5	0,21
0,75	0,21
1	0,21
1,5	0,26
2,5	0,26
4	0,31
6	0,31
10	0,41
16	0,41
25	0,41
35	0,41
50	0,41
70	0,51
95	0,51
120	0,51
150	0,51
185	0,51
240	0,51
300	0,51

This application implies the possibility to draw the metal conductor at this level with good process-ability and final quality. Normally state of the art technology for copper uses multi-wire drawing machine, where in a single pass it can be drawn 8-16-24 and more wires contemporaneously, at high production speed, i.e. 20-30m/sec, with a significant process cost reduction. In the recent years the industry, where possible, moved to Aluminum conductor, with some limitation drawing it in fine wire: 0.20-0.30mm seem to be a limit according to the different equipment available, as finest wire. Lower is more difficult. Additionally, because of the different density ratio Cu/Al 8.91/2.7, the cost per kilo of Aluminum fine wire process, assuming to process it with the same efficiency, requires 3.3 times more of drawing costs per kg, reducing significantly the cost gap between Cu and Al fine wires, normally high for high diameter wires. On this respect CCA is a more versatile conductor. Thanks to its external Copper surface it offers all the advantage of Copper drawing and better cable flexibility: in spite of Aluminum, wire to wire friction is comparable to Copper. CCA can be easily drawn in single wire and multi-wire in conventional Copper drawing equipment with minor modification in consumables, like different die profile and eventually emulsion concentration. The current experience achieved, showed productivity similar to Copper.

As per Copper, Tinned CCA improves significantly the drawing process, thanks to the lower die friction of Tin. The Tinning process of CCA showed equivalent performance of Tinning Copper process.

Definition of High quality CCA

CCA can be manufactured using hydrostatic, cladding, and plating processes [3, 4, 5, 6]. The most common method to produce CCA is cladding. High Quality CCA depends on the quality of the two metals being clad together, as well as the quality of the processing

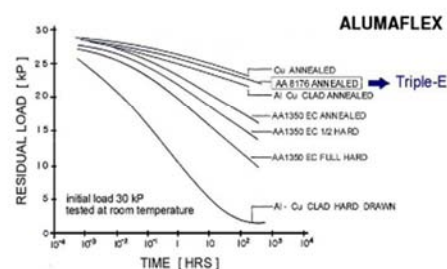
practices. Not all methods or practices will yield high quality products. The quality of the metals and cladding process are very critical to yield a true metallurgical bond. The presence of the metallurgical bond defines the quality of the CCA.

Aluminum Core

The aluminum core is very critical to ensure the high quality of CCA. Common impurities in solid aluminum are micro inclusions of steel or iron. The presence of these micro inclusions are highly detrimental in processing of CCA to fine wire sizes. Fine wire sizes can be defined as any wire size less than 0.5 mm in diameter for the purpose of this paper. Inclusions can lead to cracks, voids, wire breaks, and surface defects.

The typical aluminum grade used for electrical wire and cable applications is the 1350 Electrical Conductor (EC) Grade. Its composition is min. 99.50% aluminum; max 0.40% Fe; max. 0.10% Si; max. 0.05% Cu; and others.

This aluminum grade was used in homes from the mid-1960s to early 1970s. Using this grade of aluminum was considered a potential fire hazard and 55 times more likely to have one or more connectors reach "Fire Hazard" conditions than those homes wired with copper [1]. The reasoning was that the aluminum wire was connected to the copper connectors. Al 1350 EC has a higher creep rate than copper. The dissimilar creep rates of the two metals lead to loss of contact load and electrical degradation over a long service life. In other words, the connections are unreliable over time due to the expansion and contraction of aluminum wire. In 1968, Southwire developed and patented aluminum alloy AA-8176. This 8176 alloy has a creep rate that is similar to copper as shown in figure 2 below [7]. The similar creep rate allows this aluminum alloy to be installed inside buildings and is recognized by the NEC (National Electric Code). NEC also specified that any 600 V cables made of aluminum must be made using 8000 series. Copper-Clad Aluminum products, such as Copperlite™ CCA made with 8176 aluminum core, provides reliable and safe connectivity.



The creep properties of AA 8176 are comparable to annealed copper.

Figure 2 : Creep properties of AL 1350, AL 8176, and Copper

Metallurgical bond

High quality CCA can be guaranteed if the two metals form a verified metallurgical bond. A metallurgical bond can be defined as an atomic interdiffusion of the two metals, which in the case of CCA, are copper and

aluminum. At this interface, copper and aluminum formed an alloy. It is critical that this interdiffusion zone is free of voids, cracks, and oxide films. This bond/interface, when formed properly, cannot be mechanically separated. Figure 3 below illustrates the metallurgical bond in Copperlite™ CCA [8]. The metallurgical bond of CCA is critical to ensure further processing of the CCA wires and it is also critical in the corrosion behavior. The copper provides corrosion protection to the aluminum core. If there are voids or cracks where air or moisture can migrate in between the two dissimilar metals, it will accelerate the corrosion rate. The metallurgical bond also ensures theft prevention as the two metals cannot be easily separated mechanically. It can still be recycled or processed chemically.

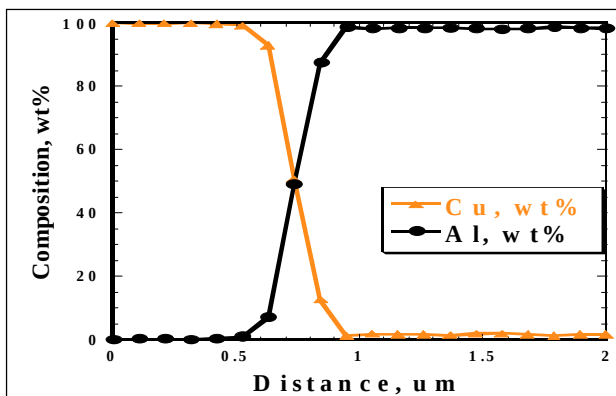


Fig. 3 : Metallurgical bond in Copperlite™ CCA

PRODUCTION OF LV PROTOTYPES WITH DIFFERENT FLEXIBLE CONDUCTORS

Following cables were produced using the conductors made with different metals:

	Cu	CCA	CCA Sn	Al
3x1,5 mm ²	X			
3x2,5 mm ²		X	X	X
1x16 mm ²	X			
1x25 mm ²		X		X

The conductors were stranded like the following (number of wires and diameter of wires, in mm.):

	Cu	CCA	CCA Sn	Al
3x1,5 mm ²	24x0,26			
3x2,5 mm ²		48x0,26	48x0,26	36x0,30
1x16 mm ²	110x0,40			
1x25 mm ²		7x26x0,41		7x28x0,39

The multipolar cables were based on the design of the typical FROR 750 V cable, according to Italian national prescriptions (CEI 20-20, 20-35 and 20-22 II for fire retardancy). In particular the flexible class 5 conductor is covered with a special flexible PVC insulation (category CEI EN 50363-3 TI2), eventually made of two layers with coloration of the only external one for efficiency purposes. The insulated cores are subsequently laid up on a single

twist lay-up machine in 3 cores formation with a defined lay pitch, then covered with bedding layer and external jacket (category CEI EN 50363 TM1, TM2, Rz; IEC 60502-1, ST2); both these layers are made of special PVC compounds, properly developed in order to achieve superior flexibility of the cable and fire retardancy performances of the category 20-22 II.

In summary, the cables with multipolar design were produced according to following production flow (downstream the conductor stranding phase) :

- Insulation (double layer in coextrusion configuration); speed around 100 m/min
- Lay-up on single twist machine
- Jacketing (double layer in coextrusion configuration - bedding and jacket); talc applied above the laid-up core for reducing sticking effect of the extruded layers; speed around 50 m/min

Finally, following dimensions were measured on the produced cables (in mm.):

	Extern. Diam.	Jacket Thick.	Filler Thick.	Insul. Thick.
3x1,5 mm ² Cu	8,77	1,29	0,17	0,696
3x2,5 mm ² CCA	10,51	1,45	0,06	0,798
3x2,5 mm ² CCA Sn	10,52	1,46	0,02	0,832
3x2,5 mm ² Al	10,32	1,52	0,15	0,690

As far as the unipolar cables are concerned these were based on the design of the typical FG7R 1 kV cable, according national prescriptions (CEI UNEL 35375 FG7R/FG7OR and CEI 20-22 II for fire retardancy). This cable is based on crosslinked insulation, made with rubber dispersed in PE phase (G7 class) and produced via the typical silane-crosslinking process, widely used for this kind of cables since more than 20 years. Downstream eventual curing phase in sauna, the insulated cores are covered with PVC jacket, applied with single layer extrusion process, and provided of special characteristics in order to comply to CEI EN 50363, TM1, TM2, Rz; IEC 60502-1, ST2). Even though the jacket material used for FG7R cables is of same category of the jacket of FROR, the FG7R jacket is characterized by superior mechanical properties and hardness, whilst the FROR material exhibits better flexibility.

In the following table the dimensions measured on the single core cables are indicated (in mm):

	Extern. Diam.	Jacket Thick.	Insul. Thick.
1x16 mm ² Cu	9,89	1,64	0,81
1x25 mm ² CCA	11,77	1,57	1,13
1x25 mm ² Al	11,48	1,43	1,05

MECHANICAL TESTS

After production the multipolar cables have been submitted to special tests in order to check the capability of the cable to sustain reverse bending cycles without significant damages or losses of functionality. This test, described in CEI 20-20 specification, is performed under following conditions:

- Length of cable sample : 5 mt
- Reverse bending at 180 ° complete cycles (round trip cycle)
- 1 mt width between fixed points
- Bending speed approximately 0,33 m/sec
- 1 kg weight is hanged at the free side of the cable under testing
- Diameter of the rolling pulleys : 80 mm for 3x1,5 mm² and 120 mm for 3x2,5 mm²
- Full current circulating in the 3 conductors of the cable under test
- Voltage continuously applied between phases: 230 V.

Hereunder a schematic view of the machine used for the reverse bending test performed with the produced cables :

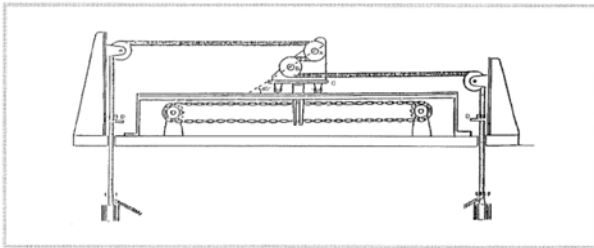


Fig. 4 : reverse bending test apparatus

The test is interrupted under occurrence of one of following conditions:

- Interruption of current circulating in the conductors
- Short circuit between the cable phases
- Short circuit between phase and rolling pulleys

This test and other mechanical tests (bending and torsion) are under execution in Prysmian laboratories.

AGEING IN AGGRESSIVE CONDITIONS

Wire integrity test

To qualify bimetallic wire quality two tests have been taken in consideration

1. prEN 3475-514

In this EC standard 2 m. CCA wire samples are immersed in concentrated (density 1,088 g/cm³) HCl solution at pH ~ -1 at room temperature. The test is passed if no H₂ evolution is detected with the naked eye during 1' immersion. Due to difficult manipulation of thin wires, 1 m samples have been tested in this case. Reference Cu and Al wires have not been tested as at prescribed pH Cu does not develop H₂ and Al corrodes with H₂ evolution.

It has been previously found that high quality CCA wires with > 1 mm diameter pass this test. In the present investigation results were as follows

Material	Wire Ext..d. (mm)	Taken from stranded conductor (mm ²)	5 x 2 m. wire samples average rating for no H ₂ (minutes)
CCA	0,26	2,5	>2,5
CCA Sn	0,26	2,5	>2,4

According to these results both CCA and CCA Sn 0,2

- mm. external diameter wires largely pass the standard.
- Alternative test to check the Copper layer integrity. In this alternative test CCA wire samples are immersed in a 4% by weight NaOH solution at pH ~ 14 at 75-85°C for 4 hours. To pass the test no visible crack or break should be detected after test with the naked eye. Reference Cu and Al wires have not been tested as at prescribed pH Cu is protectively oxidized and Al is corroded with H₂ evolution. In the present investigation results were as follows:

Material	Wire Ext. Diam. (mm)	Taken from stranded conductor (mm ²)	Five 1 m wire samples	
			PASS	NO
CCA	0,4	25,0	5	0
CCA	0,2	2,5	5	2
CCA Sn	0,2	2,5	5	0

According to these results both plain CCA 0,4 mm and CCA Sn 0,2 mm external diameter wires pass the test. Additional samples of plain CCA 0,2 mm were tested and 5 passed the test. 0,2 mm wires must be treated carefully.

The conclusion is that stranded 0,2 and 0,4 mm CCA wires are of good quality. CCA Sn wires are of superior quality.

Outdoors life test

In order to test for actual service conditions 100 mm long 2,5 mm² core lengths are clamped between standard 30 A connectors and fed with 15 A AC current 2 hours cycles while freely exposed outdoors. For each material 10 connectors in series are used (18 clamping points). The average performance is evaluated monitoring the overall potential drop with time. Both crimped and directly clamped terminations are tested for each material.

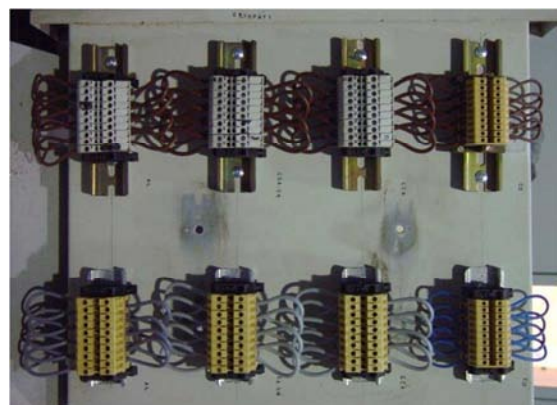


Figure 5 : Outdoor exposure test during assembly. Left to right Al, CCA Sn, CCA, Cu. Top line crimped connections, bottom line direct connections.

At the end of the test the core terminations are dismantled and examined for possible degradation. The test is still going on and results so far are reported in Figure 6.

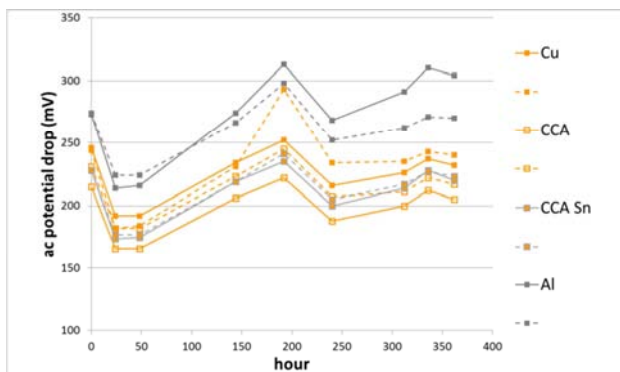


Figure 6 : Outdoor exposure, ac potential drop vs time at 18 A. Cu 1,5 mm², CCA, CCA Sn and Al 2,5 mm². Solid lines crimped termination, dashed lines direct termination.

Water exposure test

To test for flooded conditions 1 m wire samples helically wound on 30 mm mandrel have been immersed in tap water and electrode potential monitored vs time. Presence of Al corrosion products is also monitored during the test. Results are reported in the table and graph below.

Material	Wire ext.diam . (mm)	From stranded conductor (mm ²)	Hours for visible Al corrosion spots on 2 wire samples 1 m length
CCA	0,4	25,0	50 – 100
CCA	0,2	2,5	50 -100
CCA Sn	0,2	2,5	500

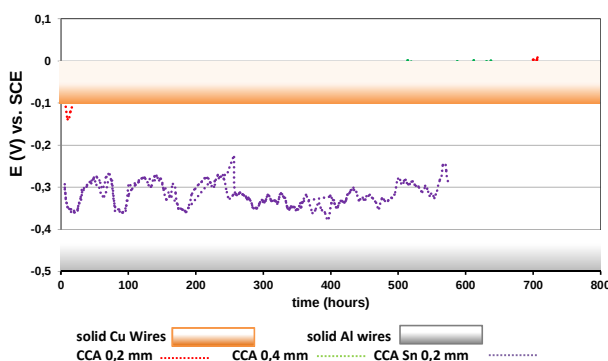


Figure 7 : Tap water exposure test, electrode potential vs time

Plain CCA shows a limited resistance to flooded conditions. However no significant electrode potential change can be detected. This means that the exposed Al area at defects and relevant galvanic current are very small.

CCA Sn shows significantly higher resistance in flooded conditions.

The solid Cu - solid Al potential difference (~ 0,4V) is > than the CCA Sn – solid Al potential difference (~ 0,15 V). This explains why CCA Sn results in less Al corrosion at defects than with plain CCA.

Conclusion is that these conductors can withstand water immersion for limited periods only, the maximum being

about 20 days with CCA Sn.

CONCLUSIONS

Copper clad aluminum is an attractive alternative to copper. It provides a more economical light weight product as compared to copper. The quality of CCA is very critical in several applications. Key components to ensure high quality CCA are the quality of the metals such as copper and aluminum and the integrity of the metallurgical bond.

Prototypes of LV cables were produced using Cu, CCA, CCA Sn and Al flexible conductors.

Tests were performed in order to assess the integrity of the CCA and CCA Sn wires used for the production of the prototypes, with positive results. Two methods are proposed by immersion of the wires in 2 different solutions and in modified conditions. CCA Sn showed superior properties also on small wires (0,2 mm.).

A special outdoor life test was defined and set-up with the cable prototypes, aimed to understand the behavior of the different conductors in realistic installation and severe ambient conditions. Results so far achieved demonstrate the potentiality of application of CCA as flexible conductor for electric LV power cables.

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