Concrete Structures' Repair Procedures

Standards and Recommendations

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Abstract

The main objective of this dissertation is to summarize the execution procedures of the repair methods of concrete structures and posteriorly their application on a case study.

In order to achieve a durable and effective repair it is important to eliminate the cause of deterioration. Hence, the first issue addressed in this dissertation was the identification of the structures' deterioration mechanisms indicating, for each of them, which were the possible repair methods. Besides that, it is essential to make an adequate surface preparation, to ensure a good bonding between the repair material and the existing material. Therefore, it was necessary to identify the various removal and cleaning methods for concrete and reinforcements. Posteriorly, a brief description of each repair technique was presented along with the respective execution procedures, relating them with the available standards and recommendations.

Lastly, an intervention proposal for the rehabilitation of a structure was prepared. A detailed visual inspection was performed, based on previously done tests, where it was concluded that the concrete was delaminated and the reinforcements were corroded, due to carbonation and chlorides. Since the degree of contamination wasn't high, it was concluded that the electrochemical processes weren't an economical viable option for the owner, because the intervention costs were high. Therefore, a coating of the contaminated concrete areas was chosen, since this technique is effective and of lower cost. In the remaining areas, the substitution of concrete and application of a surface protection was performed, in order to avoid the recurrence of corrosion.

Introduction

Currently, there are no normative regulations regarding the execution procedures of concrete structures' repair, in Portugal. The only existing standard is the NP EN 1504. This standard presents the products and systems used in concrete protection, including recommendations concerning surface preparation, procedures and quality control, however it does not specify the execution procedures for repairs. Therefore, the interest to elaborate a gathering of the most recent standards and recommendations on this matter arises.

Protection and repair

Before deciding which repair method to adopt, it is of the utmost importance to understand what originated the defects on the concrete in order to be possible to eliminate the cause. Therefore, just repairing the defects isn't enough, since the defects will reappear if the cause isn't corrected and so the repair will not last. This is one of the core principles to assure an effective and durable repair.

The main deterioration mechanisms affecting concrete structures are: reinforcement corrosion due to carbonation and chloride contamination; chemical deterioration processes (by sulphates; alkalis; acids; soft waters and ammonium and magnesium salts; and sea water); biological attack; erosion, abrasion and cavitation; freeze/thaw and fire.

The repair of the structure should be done after identifying the deterioration’s root causes. This repair process includes concrete surface preparation, execution procedures and quality control for the repair method.

Concrete surface preparation should always be performed in order to promote an effective bonding between the repair material and the existing concrete surface. Hence, if not correctly executed, it could jeopardize the repair process. This preparation will vary according to the type of repair to adopt and the condition of the concrete and reinforcements. For that reason, removing the deteriorated concrete and cleaning the remaining should be performed before proceeding to the repair. In general, the concrete surface should be left clean, sound, dry and with a rough texture.

Concrete surface cleaning can be done with chemical methods, mechanical methods, shot blasting, blast cleaning or acid etching. Regarding reinforcements, they should be cleaned with a wire brush, sand jet or high pressure water. Concerning the removal of concrete, the most frequently used methods are the following: hydro-demolition and hydraulic, pneumatic and electric hammers.

EN 1504-10 defines a series of tests to verify the quality of products and systems used before, during and after the repairs for each method [1] (with the exception of electrochemical methods and corrosion inhibitors).

Below are presented some of the protection and repair methods studied in the scope of this work.

Surface protection systems

Surface protection systems are used to prevent the penetration of aggressive substances, water or other liquids, chemical and biological attacks, among others. These systems can also be used in the repair when combined with other methods.

According to EN 1504-2, the three methods of surface protection are hydrophobic impregnation, impregnation and coating [2].

Hydrophobic impregnation creates a water repellent layer thus reducing the penetration of water in the concrete. However it does allow the evaporation of water through the coating contributing, this way, to the reduction of humidity inside the concrete. Reducing the humidity content inside the concrete lowers its conductivity, thereby increasing the resistivity of the electrolyte.

Impregnation results of the application of a low viscosity liquid product that is absorbed and partially or totally fills the concrete’s pores and capillaries. This way, surface porosity is reduced and the concrete surface is reinforced. This treatment produces a discontinuous thin surface zone on the concrete’s surface that hardens and, in some cases, with the increase of resistance to wear, limits the effects of abrasion [2].

The purpose of the coating procedure is to produce a protective continuous layer over the concrete’s surface [2].

These methods can be used to prevent or reduce the corrosion of reinforcements by chlorides or carbonation, sulphates attack, alkali-aggregate reactions, abrasion-erosion, freeze-thaw, acid attack or biological deterioration. Nevertheless, since hydrophobic impregnation allows the penetration of carbon dioxide and lowers the humidity content on concrete it can lead to an increase in carbonation rate.

- **Surface preparation**

Step 1: Check the concrete’s surface condition. If it is deteriorated, the concrete replacement method should be applied, before using surface protection methods.

Step 2: Clean the concrete using water jetting, for example.

- **Impregnation and hydrophobic impregnation execution procedures**

Step 1: Prepare the material mix, following the recommendations of EN 1504-10 [1];

Step 2: Apply one layer with a trowel in order to level the surface and cover the voids;

Step 3: Apply a primer with a brush (optional) [3];

Step 4: Apply the material from bottom to top, by pulverization, under vacuum, or through a gel [1]. EN 1504-10 states that the penetration of hydrophobic impregnation (by means of a silane or siloxane) may be improved when the material is applied on two phases (wet on wet) [1].The penetration should be continuous with at least 2 mm of thickness [3].

- **Coating execution procedures**

The execution procedures relative to coating will be described in the case study.

Electrochemical methods

These methods are based on the alteration of the reinforcement's potential through the application of an electric field. The three electrochemical techniques used to repair structures due to corrosion are: cathodic protection, chloride extraction and re-alkalization. The main differences between these three methods are the length of treatment and the electrical current applied. While on cathodic protection the repair application is permanent, on chloride extraction the length of treatment varies from 2 to 8 weeks and on re-alkalization from 2 to 10 days. With regard to the intensity of current applied, on cathodic protection its value is approximately 10 mA/m^2 and 1 A/m^2 on the remaining techniques.

Cathodic protection consists in the supplying of electrons to the reinforcement through a direct current; consequently, the reinforcements' negativity potential is increased turning them into a cathode. This way, it is possible to prevent or reduce the corrosion affecting the reinforcements. This technique can be applied by impressed current or sacrificial anodes.

Chloride extraction main principle is the restoration of the passive film on the steel reinforcements through the reduction of the chlorides in the interior of the concrete.

The main principle of re-alkalization is the restoration of the medium's alkalinity, in order to recover the reinforcement's passive film. This method cannot be used when the cause of deterioration is contamination by chlorides. However, it is appropriate when carbonation is the cause of the problem.

These techniques are highly effective in the control of corrosion over time and avoid the removal of contaminated concrete. On the other hand, electrochemical methods shouldn't be applied in prestressing concrete, due to the weakening of steel. The use of these methods isn't recommended in structures deteriorated by reactive aggregate, since the increase in the medium's alkalinity can stimulate the occurrence of alkalis-aggregate reactions [3].

The chloride extraction procedures are presented below.

- **Surface preparation**

Before performing the chloride extraction it is important to identify defects, such as the possible delamination of concrete and the existence of cracks, since that, in order to apply a uniform current, the reinforcements must be electrically connected to each other and the concrete's current distribution must be adequate and homogeneous [3]. All of the previous repairs must also be identified and the depth of chloride contamination and carbonation must be determined [3].

As previously mentioned, in this type of repair the removal of contaminated concrete isn't necessary. However, the concrete should be cleaned in order to remove superficial dirtiness. When the reinforcements are already corroded and the concrete delaminated or with cracks, it is important to repair it with cement-based materials before proceeding to the chloride extraction, to assure that the distribution of current is as uniform as possible. It is also essential to remove previous repairs with insulating characteristics so that the current can be properly distributed through the structure.

- **Execution procedure**

CEN/TS 14038-2:2011 specifies the minimum requirements for the investigation of the concrete and reinforcement's condition before, during and after the treatment project by chloride extraction [4]. The execution procedure is presented below [5].

Step 1: Anode and electrolyte application to the concrete's surface;

Step 2: Application of a direction current between the cathode (reinforcement) and the anode and installation of a power source;

Step 3: Testing to verify the absence of short-circuits between the anode and cathode and monitoring of the system's functionality;

Step 4: Sample extraction to determine and analyze the chloride content at the reinforcement level;

Step 5: When the chloride content is lower than 0,4% (cement weight), the electric current should be cut, removing the whole repair system and proceeding to the cleaning of the concrete's surface.

Step 6: In the end, apply a surface protection system to avoid the re-contamination of the structure by chlorides.

- **Control**

During the whole electrochemical chloride extraction process a continuous record of the applied current's density should be kept and this shouldn't exceed 10 A/m^2 [3]. Besides that, samples of the concrete's surface should be taken and analyzed in order to verify the decrease in chloride content. It is also very important to regularly verify the electrolyte and this should be replaced whenever necessary.

In order to ensure the durability of this repair technique, even after this process is completed, periodic inspections should be done.

Concrete replacement

Concrete reposition consists in the replacement of damaged or contaminated concrete by a repair material. Generally, this method can be applied in every deterioration mechanism and its objective is the improvement of the original structural capacity of the deteriorated concrete or to simply resolve aesthetic problems. According to EN 1504-10 there are three methods available to perform concrete placement: hand-application of concrete or mortar, shotcrete, recasting of concrete (dry pack, form and pump concrete, cast-in-place concrete or grouted preplaced aggregate) [1].

The surface preparation procedures of the concrete will be described in the case study. Below are presented the procedures of some of the techniques of concrete replacement (the cast-in-place concrete and the shotcrete will also be described on case study).

- **Hand-applied concrete or mortar execution procedures**

Step 1: Mix the repair material, according to EN 206-1 [6] and ENV 13670-1 [7];

Step 2: Apply a thin layer of the repair material on the saturated surface dry to fill the pores, in order to improve bonding. In case a bonding primer was applied, this step can be ignored;

Step 3: After that, the first layer of repair material is applied with a little pressure using a trowel so that it stays compact and without air pockets;

Step 4: Posteriorly, the necessary successive layers are applied until the desired thickness is obtained. According to EN 1504-10 the layers should be applied wet on wet. However, if the application of the layers is interrupted, the previous layer should be prepared once again before applying the next layer [1]. Note: it is important to fully encapsulate the reinforcement in order to avoid the formation of voids and not jeopardize the durability of the repair;

Step 5: Level the last layer with the adjacent concrete;

Step 6: After that, perform the curing of the concrete (keeping in mind the recommendations of EN1504-10 [1]).

- **Execution procedures of grouted preplaced aggregate**

Step 1: Start the erection of the formwork with anchors;

Step 2: Wash the aggregate. They must be rolled and gap graded to ease the injection of grout;

Step 3: Deposit the aggregate into the formed cavity, trying not to let them fall more than 1.5 m, except when the repair happens under water and the aggregate fall through water [8];

Step 4: When the cavity is filled of aggregate, finish the formwork's erection. This is equipped with valves and pipe nipples to connect the hose to the pump;

Step 5: Mix the grout and place it into the pump;

Step 6: Pump the grout from the bottom to the top, in order to fill the voids between the aggregate. The external vibration may help in the consolidation, however it isn't necessary when the aggregate have a suitable granulometry and the quality of the grout is good [8];

Step 7: When the cavity is filled with the grout, the pressure should be slightly increased to avoid bleeding problems and to consolidate the repair material. However, if the grout is spilling out of the forms, the pressure increase should be stopped and the pump shut down [8];

Step 8: Perform the curing of the concrete (keeping in mind the recommendations of EN1504-10 [1]) and remove the formwork.

Case Study

In order to have a better understanding of the mechanisms of deterioration and methods of protection and repair, an intervention proposal will be elaborated in this chapter for the *Pórticos das Pontes Rolantes* in Portugal.

The *Pórticos das Pontes Rolantes* are composed by four beams supported in columns, allowing the operation of the two rolling bridges, where the columns are placed in three line-ups. In the central line-up the columns support two beams and in the laterals they support one beam. The columns and beams are composed by reinforcement concrete and the structure is exposed to the marine environment (XS1). The construction was finished in 1973/1974 and over the years many constructions of these shipyards showed deterioration signs. The visual inspection and tests were performed 25 years after its construction.

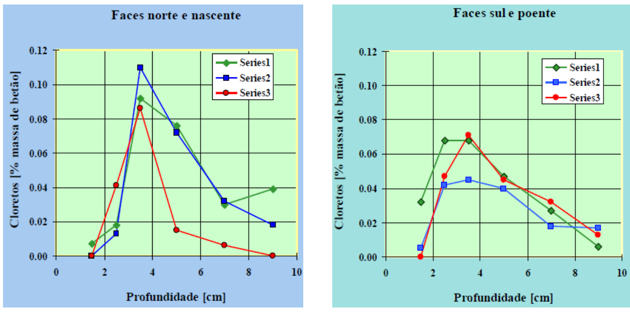
Anomalies description

In the first place it is necessary to evaluate the state of the structure, in order to define the kind, the causes and the level of deterioration. For that purpose, it's important to perform a visual inspection to the structure and a more detailed inspection through a few tests.

On the visual inspection it was concluded that the anomalies in the construction, regarding the material's deterioration, were the delamination of concrete and reinforcement corrosion.

The detailed inspection was performed through tests, namely the bar cover, chloride profile, carbonation depth, concrete resistivity and corrosion rate.

In the carbonation test the following results were obtained: 6 to 11 mm for the beams and 14 to 28mm for the columns. The difference in carbonation depth of columns varies in more than double than the one of the beams. This difference is due to the fact that the concrete in beams has better quality than the one in the columns. Regarding the thickness of the bar cover test, in beams the values obtained were 10 to 30 mm and 20 to 50 mm in the columns. In general the thickness of bar cover between the beams and the columns doesn't differ much, but in this case a big difference of results was obtained. This difference could be associated with a problem of deficient execution during construction. It was concluded that the presented results were inferior to the recommended minimum.



(a) (b)

Figure 1: Chloride profile on the faces: a) north and east; b) south e west

Figures 1a and 1b illustrate the chloride penetration profile in the following faces, respectively: north and east; south and west. Observing the obtained results it was concluded that the chloride content on the north and east faces is greater than the chloride content on the south and west faces. This happens because usually, when it rains, the dominant wind blows from the south and west. Thus, when it rains on these faces (south and west), the chlorides deposited on the surface are washed out, leading to a decrease on the free chlorides present on the concrete's pores. On the other hand, the north and east faces aren't subjected to that kind of wind exposure and so the chlorides build up on those faces. Therefore, the chloride content on these faces would be expected to be greater to that of the south and west faces.

The critical chloride content in the concrete is generally 0,4% of the cement's weight. However, the values obtained in the figures are relative to the percentage of concrete mass. A general concrete has 300 kg of cement per m^3. Therefore, the critical content of chlorides in these conditions takes a value of 0,05% of the concrete's weight. When re-observing the obtained results it is possible to conclude that the chloride content present in the structure is greater than the critical value, even though it isn't a high quantity.

In the beams, the concrete's resistivity obtained was 5 to 30 kΩ.cm and 1 to 67 kΩ.cm on the columns. Notice that this test was taken during spring when the environment was drier. Since the resistivity values are relatively high, the corrosion rate is expected to be low.

The corrosion rate obtained on the test was 0.9 to 2µm/year. This is a relatively low result. This value is concordant with the obtained results on the concrete resistivity test, since as the test was done during spring, with lower relative humidity levels, the rate of corrosion is controlled by the electrolyte i.e. by the concrete's resistivity. In case a broader vision regarding the rate of corrosion is desired, several tests should be performed in different times of the year, namely, one per season.

Intervention proposal

Taking into account the anomalies mentioned above, it is necessary to choose the intervention methods to repair them. Regarding reinforcement corrosion (due to chloride contamination and carbonation), several options can be chosen, such as the replacement of the deteriorated elements, the reduction or annulment of the rate of corrosion or the demolition and construction of a new structure. This last option is of no interest since the structure can be repaired.

The corrosion rate can be reduced through electrochemical methods, total concrete substitution, corrosion inhibitors or with a surface protection system.

The advantages of the electrochemical methods over the traditional methods are the avoidance of the removal of contaminated concrete (not delaminated) and the fact that the results they produce last longer and are more effective when it comes to controlling corrosion over time. However, the intervention costs are, in general, higher than those of the traditional methods. The re-alkalization is not an option to consider because besides the carbonation, the reinforcement's corrosion is also due to the presence of chlorides. In this case, cathodic protection could be applied, however it was decided that it wouldn't be since it requires significant monitoring over time and a high cost. Lastly, the chlorides extraction would be a viable option, since it removes chlorides and increases the structure's pH. Besides that, it doesn't require periodic monitoring like with cathodic protection, though it does result in significant costs. Between electrochemical extraction of chlorides and the total replacement of contaminated concrete, it would make more sense to choose the first, because if the repair doesn't remove all of the contaminated concrete, new corrosion zones can form on the adjacent regions to those repaired, leading to a continuing deterioration.

Corrosion inhibitors are products that are added to control the depassivation of the reinforcement, delaying the corrosion process. However, they aren't applied in this case because the reinforcements are already depassivated.

Lastly it's possible to choose to apply a surface protection to maintain a low water content and to decrease the corrosion rate. This is a technique that involves some risks, but it does have a much lower cost when compared to the previous methods. This technique is only viable because the chloride contamination isn't very high and the corrosion rate is relatively low, as verified in the tests performed. Besides that, this method will also prevent the penetration of aggressive agents through the surface, thus avoiding a recurrence of deterioration. It is important to refer that only the coating can be applied, since if hydrophobic impregnation is applied, the carbonation rate could increase (this type of impregnation allows the diffusion of carbon dioxide and reduces the concrete's water content).

Therefore, the application of a surface protection system in the areas where the concrete is contaminated was chosen to control the corrosion of reinforcements. The concrete should be removed and replaced by a high quality concrete and with adequate bar cover in the areas where the concrete is delaminated. After the concrete's replacement, a surface protection can be applied to prevent the penetration of aggressive agents and avoid the recurrence of corrosion.

Procedures

The concrete replacement was performed through cast-in-place in the cantilever and inferior faces of the beams and with shotcrete on the faces of the columns. A paint coating that prevents the penetration of aggressive substances and increases the concrete's electric resistivity was chosen on the surface protection system.

- **Surface preparation**

First of all, the delaminated areas are identified using a hammer, knowing that when they are tapped and sound hollow this indicates the presence of delaminated concrete. After that, the perimeter of the area to repair is marked, keeping in mind that the tracing should be as simple and uniform as possible, refraining from marking excessive corners and acute angles (Figure 2a). After that, the sawcutting of the marked perimeter is performed, trying not to damage the reinforcements (Figure 2b).

(a) (b)

Figure 2: Surface preparation: a) marking of perimeter of the zones to remove; b) sawcutting of the marked perimeter

The deteriorated concrete can be removed by hydro-demolition or with a pneumatic hammer, carefully so as not to damage the surface (in areas of difficult access). Figure 3a illustrates the removal of concrete with a pneumatic hammer. The concrete involving the corroded reinforcements must also be removed (Figure 3b), in order to expose the totality of the reinforcements. The minimum distance between the reinforcement and the remaining surface must be of 15 mm or the maximum dimension of the repair aggregate plus 5 mm, choosing the higher value.

Lastly, proceed to the cleaning of the reinforcements and concrete surface. For that, in larger areas, the reinforcements are cleaned with a dry sandblasting (this method is very effective, since it can clean the area behind the reinforcements by rebound) and in small areas using a wire brush. The concrete's surface should be cleaned using water jetting in order to remove all kinds of superficial dirtiness, dust, oils, among others.

a) b)

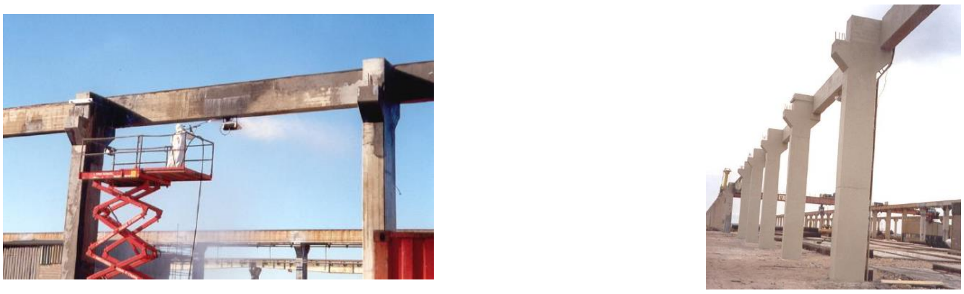
Figure 3 - Removal of concrete: a) with a pneumatic hammer; b) in the area involving the reinforcements

- **Execution procedures for the repair of the delaminated areas with shotcrete**

First of all, the mixed repair material is made, according to the specifications of EN 206-1 [6] and ENV 13670-1 [7]. The repair material must abide by the shotcrete standards EN 14487-1:2005 [9] and EN 14487-2:2006 [10]. Then, in order to prove the correct route to the exit of the nozzle, air (and only air) is inserted in the hose. The material is placed in the shotcrete machine and water is inserted in an adequate amount to promote the mixture's hydration. After that, the repair material is shot as perpendicular to the surface as possible, whenever possible. After shooting all of the repair material, as soon as the material has set, the excess material should be removed with a trowel. Then, the curing takes place, keeping in mind the directions of EN 1504-10 [1]. Figure 4 shows the structure's visual aspect after replacing the concrete with shotcrete.

Figure 4: Replacement of concrete with shotcrete on the faces of the columns

After that, cleaning of the surface by water jetting (Figure 5a), in order to apply the coating, is performed. First of all, the material mix is prepared, keeping in mind the directions of EN 1504-10 [1]. Then, a primer is applied with a brush. Lastly, the protection material is applied with a trowel. The layers can be applied wet on wet. Figure 5b illustrates the visual aspect of the structure after applying the surface protection.



(a) (b)

Figure 5: (a) Cleaning of the surface by water jetting; (b) Superficial coating with paint

- **Repair procedure of the areas delaminated with cast-in-place concrete (beams and cantilevers)**

First of all, the assembly of the formwork is performed, taking into consideration that it is necessary to place openings to allow the placement of material behind the formwork and follow the directions of ENV 13670-1 [7]. After that, the mixture of repair material is made, according to the specifications of EN 206-1 [6] and ENV 13670-1 [7]. The material should be placed in the opening of the formwork and as soon as the cavity is filled, internal vibration should be applied, in order to consolidate the repair material. Then, the curing of concrete takes place and the formwork is removed. After that, the cleaning of the surface is performed with water jetting to allow the application of coating. The procedure is analogous to the one performed in the previous procedure.

- **Repair procedure of the contaminated areas with the application of a coating**

As soon as the preparation of the surface is finished (in this case, it was only necessary to clean the concrete using water jetting), the coating should be applied. The mixture of the material is prepared, taking into account that it should be a material that decreases the permeability of the concrete and prevents the penetration of aggressive agents. Besides that, it is necessary to follow the directions of EN 1504-10 [1]. After that, a first layer should be applied to level the surface and cover the existing voids. Then, a primer is applied with a brush. Lastly, the repair material is applied with a roll. The layers can be applied wet on wet.

- **Control**

EN1504-10 defines a series of tests to verify the quality of the products and systems used before, during, and after the repairs [1].

Conclusion

With this dissertation it was concluded that, for an effective and durable repair, it is necessary to: know the causes of deterioration, in order to eliminate them; prepare the surface adequately; choose suitable and good quality materials; follow the recommended execution procedures, consulting the mentioned standards (NP EN 1504, for example), for each type of repair; and lastly, perform the quality control tests, in order to verify the efficiency of the used products and systems before, during and after the repair of the structure.

The case study concerned the *Pórticos da Pontes Rolantes em Portugal*. Taking into account the anomalies of the structure (concrete delamination and reinforcement corrosion) due to the carbonation of concrete and chloride contamination, it was concluded that, considering the cost involved, the most suitable intervention on the contaminated areas would be the application of a surface coating and on the delaminated areas it would be the replacement of concrete and, posteriorly, the application of a coating that would prevent the penetration of aggressive substances. Since the contamination wasn't very high on the structure, the elected method was the surface protection. This technique carries a few risks, however its cost is inferior. This protection also has the advantage of preventing the penetration of aggressive agents, thus avoiding the restart of the deterioration.

With this dissertation the compilation of the existing information that was found scattered was achieved, so as to define the execution procedures and quality control of concrete structures repair, following the available standards and recommendations. In the future, it could be interesting to create a unique document that involves all of the aspects of this dissertation.

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