Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 3, No. 6, June, 2017

Classification of Precast Concrete Segments Damages during Production and Transportation in Mechanized Shield Tunnels of Iran

M. A. Shayanfar [a], P. Mahyar [b*], A. Jafari [c], M. Mohtadinia [d]

[a] *Centre of Excellence for Fundamental Studies in Structural Engineering, Iran University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran*

[b] *PhD Candiadte, Department of Civil Engineering, Iran University of Science and Technology, Tehran, Iran*

[c] *Associated Professor, School of Mining Engineering, University of Tehran, Tehran, Iran*

[d] *Graduated Student of MSc, School of Mining Engineering, University of Tehran, Tehran, Iran*

Received 21 April 2017; Accepted 20 June 2017

Abstract

Precast concrete segments used in shield tunnel linings are prone to damage in many situations. These damages can occur at different stages such as fabrication in segment factory, transportation to tunneling site, during tunneling process, and at serviceability stage. The aim of the present article is to study the damages inflicted on concrete segments during production and transportation, and to present a new classification of these damages throughout the two stages. The developed classification is based on field observations and examinations of major subway and water conveyance mechanized shield tunnels of Iran, located in Tehran, Tabriz, Mashhad, Kermanshah (Nosood) and Isfahan (Golab). The quality of tunnel lining suffers from what, as a direct consequence of any damage to concrete segments, during production and transportation, which will be also discussed in this article. For further investigation, more than 250 concrete segments from Tehran subway line 3 and 350 segments of concrete segments from Tehran subway line 7 were selected and studied for a statistical analysis of chipping and crack, consecutively. Absence of preventive measures to limit segment damages in precast segment factories is one of the main reasons for increased number of damaged concrete segments, and as a result, increased costs of tunnel construction at later stages. In this paper, production phase damages and factors contributing to these damages are studied. According to the findings of the study, the human (operator) error was the most important cause for chipping, and, time-dependent behavior of concrete was the essential reason in crack of precast segments. Eventually, final section of the article presents practical solutions for reduction of damages during fabrication and transportation of concrete segments.

Keywords: Concrete Segments; Statistical Investigation; Concrete Segments Damages; Chipping; Cracking.

---

1. Introduction

Concrete segments are employed as lining system in tunnels, which are excavated by TBMs (Tunnel Boring Machines). The segments are fabricated in segment factories and transported to the tunnel for being installed by the boring machine [1]. Various standards are provided for different aspects of precast concrete segments, which are used

---

* Corresponding author: payman.mahyar@civileng.iust.ac.ir

➢This is an open access article under the CC-BY license (https://creativecommons.org/licenses/by/4.0/).

© Authors retain all copyrights.

in shield tunnels. These standards could be applied for production and utilization of the elements as lining [2]. A variety of damages threaten the parts from the very beginning of the production stage to the final stage of serviceability, due to different reasons. The damages done incurred them would affect the durability of lining and in most cases impose substantial costs to the project for repairing the damaged parts. A classification of damages during excavation of shield tunnels was proposed by Japanese Society of Civil Engineering which is based on the questionnaire survey of 50 construction sites of 15 Construction Companies[3]. In this classification, longitudinal cracks and chippings in segment corners were concluded as the most common damages of the segments. Another classification was proposed by Blom [4]. In this classification, various damages that result in chipping and crack of concrete segments in the tunnel are described and also analytic solutions are proposed for illustration of the crack mechanism of concrete segments in the tunnel. Numerical modeling of the particular damaging mechanism of segmental lining especially during excavation stage of the tunnel is another subject that is studied by some researchers. Crack caused by contact deficiencies, erection tolerances, boring machine’s thrust jacks, dislocation of the segment in a ring, etc. are investigated by the developed method [5-8]. According to the past researches, qualitatively unsuitable concrete segment which is produced in the factories account for 10% of damages arise in the lining of shield tunnels [7]. The nature of the damages, which take place on the parts while being produced and transferred are those, which could be reduced considerably by presenting a careful quality control system along with an appropriate mixing design and curing method. To achieve the research goal and downgrade occurrence of the damage in concrete segments, suitable quality control methods have been discussed in some papers [9, 10]. Figure 1. shows production process of precast segments proposed by international tunnel association (ITA) [11]. As it can be seen in the figure, for fabrication of standard precast concrete segments, seven inspections are needed during various steps [11].

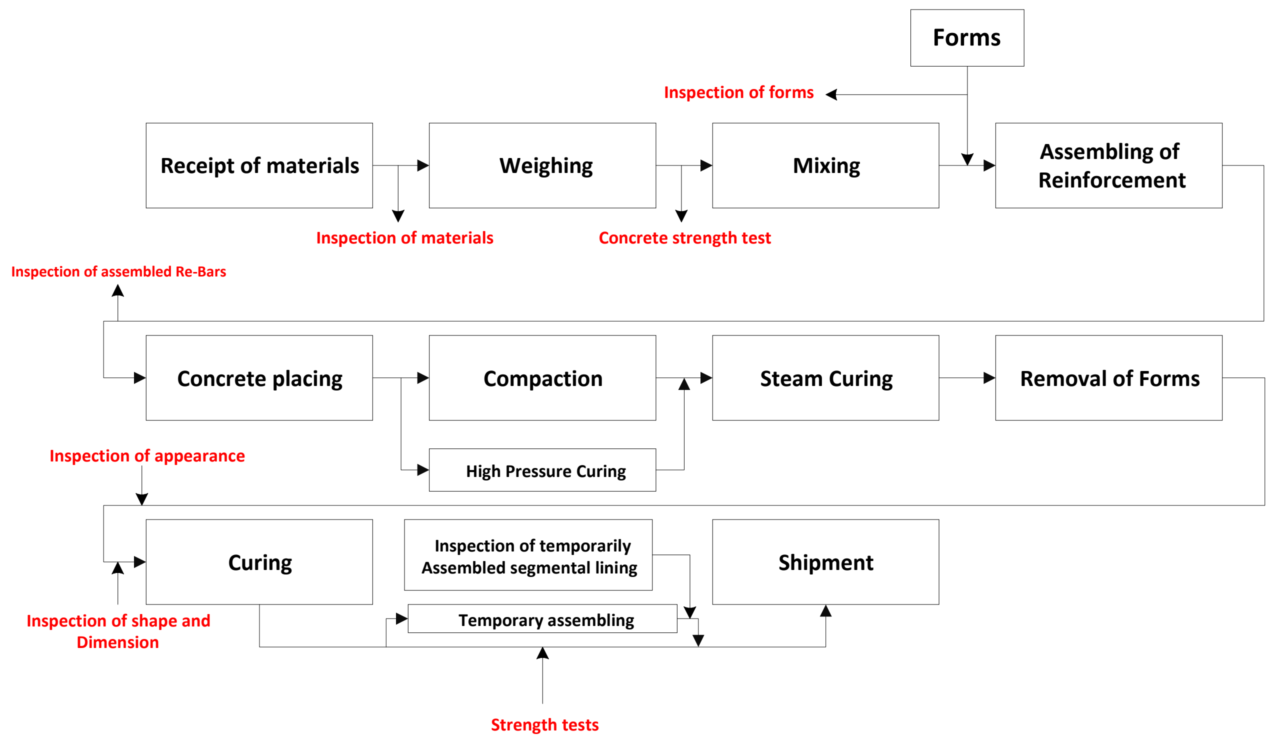


Figure 1. Sequence of manufacturing of precast concrete segments [11]

Since concrete segments are cured under certain conditions, known as accelerated curing, they achieve the required strength that in most cases is done by utilizing steam in the process. Hence, faultless curing of concrete segments using steam plays an important role in dropping destructions in the products. A typical steam curing consists of 1) initial delay prior to applying steam which is about 3 to 5 hours for getting some hardening of concrete, 2) heating period with the rate of 10 to 20 °C per hour to increase the temperature to the maximum level between 60 to 70 °C. Temperatures above 70 °C should be avoided because it results in delayed ettringite formation, leading to expansion and crack in the hardened concrete, 3) steaming period with maximum temperature for about six hours 4) temperature decrease period with the rate of 20 C° per hour for about two hours [12, 13]. Numerical modeling is also proposed by some researchers to design steam curing procedure [14]. Finally, practical guidelines for providing a standard accelerated curing can be found in concrete standards like AASHTO, ACI 517, MC90, NPCA and PCI [15-17]. Investigation of production dimensional tolerances is another subject which is briefly studied. It is essential to maintain optimum dimensional tolerances of concrete segment, which are associated with the conditions of execution of the project, and, meanwhile these tolerances might be influenced by some factors such as shrinkage of concrete, temperature difference between the concrete and surrounding environment, unfit mold and so many other factors, that causes the segments to deviate from perfection. The case could be followed by getting damaged parts and their broken gasket grooves [18, 19]. Regarding stacking of concrete segments in temporary or permanent warehouse, some famous manufacturers of TBMs, including Herrenknecht and Selli which are constructor companies of line 3 and 7 of Tehran subways respectively, have offered some effective advice [20, 21].

Generally, the concrete segments are subjected to several damages in each and every sequence of the four steps, beginning with manufacturing at the factory, transporting to the tunnel, installation at the tunnel and serviceability stage. Since the concrete segment factory is considered as the very first step taken to construct a tunnel, so getting to know the applied damages at this stage needs a well-deserved attention. It should be kept in mind that the damages imposed to the concrete segments at the production site, makes the segments vulnerable to further damages later in the other phases of tunnel excavation. That is, the share of low-quality concrete segments is, generally, more than 10% as mentioned before, even though the effects are indirect. Previous researches have indicated that no classification has been introduced, so far, in relation to damages imposed to the concrete segments especially in the production stage. Presenting such classifications would be a great help for recognition of damages imposed to these segments in fabrication plant, which helps to come up with proper solutions to reduce them. This article at first develops a new and complete categorization of damages that might happen to concrete segments in the production, transportation and tunneling stages. The proposed categorization is based upon some field and observation studies in the projects sites of line 1 of Tabriz subway, line 2 of Mashhad subway, lines 3 and 7 of Tehran subway and water conveyance tunnel of Nosood and Golab, as well as intensive inquiries among several reports of similar tunnel projects. Consequences of each damage occurred in concrete segments, while producing and transferring to the tunnels, on the quality of the lining will be examined in this article. For a further appraisal, 282 concrete segments selected from line 3 of Tehran subway and 342 segments from line 7 of Tehran subway were examined for chipping and crack, respectively. And finally, approaches to prevent the occurrence of the above-mentioned damages are discussed in the final section of the article.

2. Classification of Damages Occurred in the Concrete Segments at the Production and Transportation Stages Based on Field Studies

Figure 2. illustrates classification of damages occurred in the concrete segments at production plant and transportation stage. This categorization is based on the field studies conducted in the field of various projects: line 1 of Tabriz subway, line 2 of Mashhad subway, lines 3 and 7 of Tehran subways and water conveyance tunnels in Nosood and Golab. As it can be seen in the following chart, damages occurred in the concrete segments at production stage can be, generally, explained by two major sources of improper concrete production and operational errors and damages in the transportation stage. This is classified under a single title, chipping and crack of the segments, which is described as the resu of the operator's mistake (operational error).

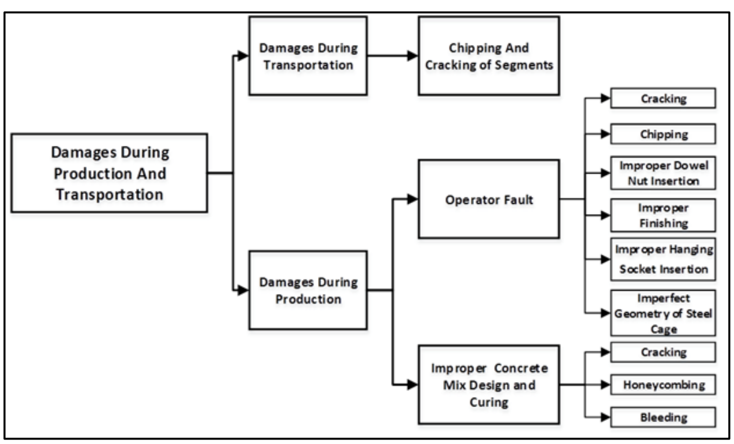


Figure 2. Damages of concrete segments during production and transportation

Figure 3. shows damages of concrete segments occurred at production stage. The photos have been taken from mechanized shield tunnel projects in Iran.

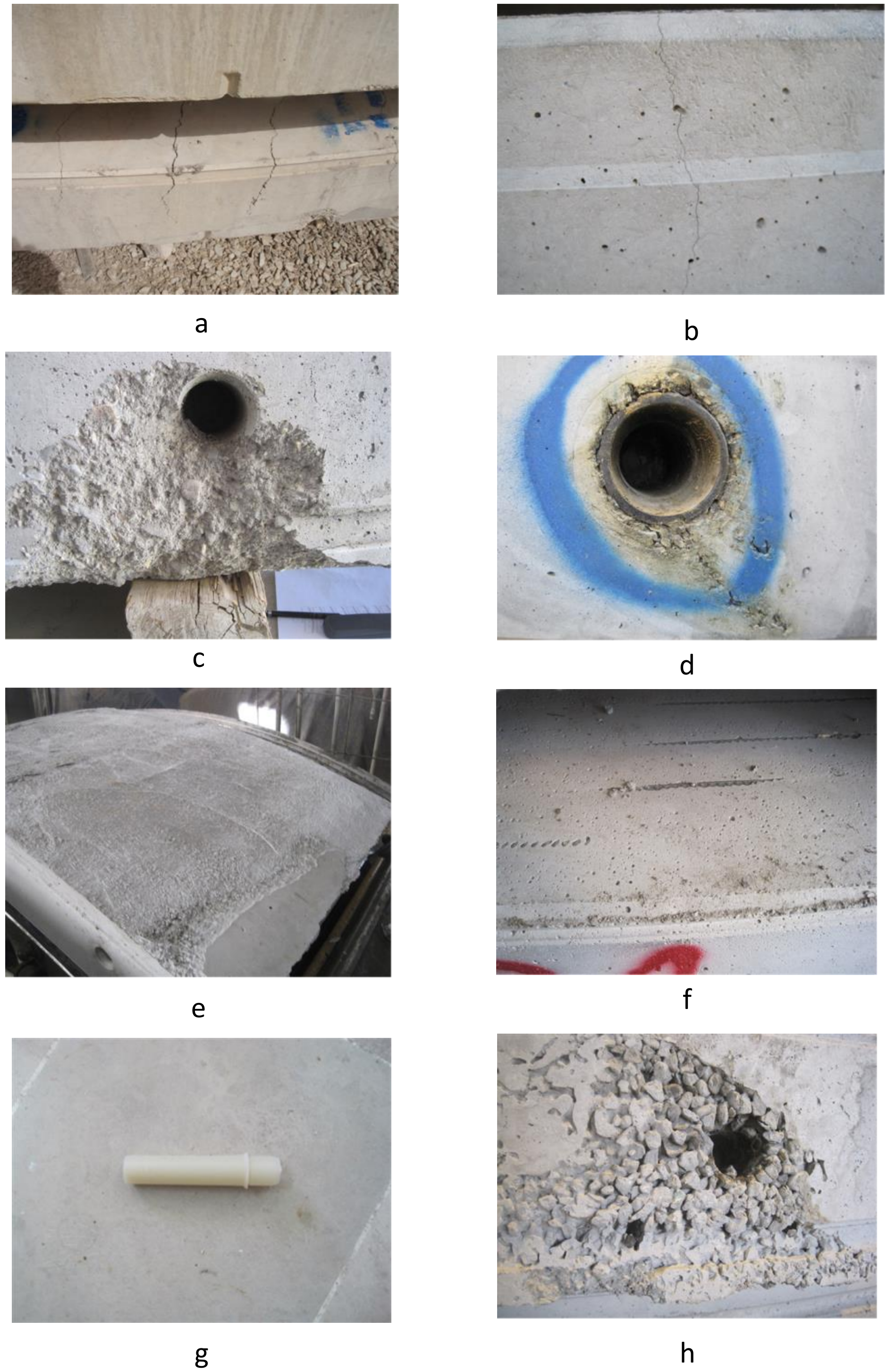


Figure 3. Damages of concrete segments during production, a: crack due to operator fault (Nosood water conveyance tunnel), b: crack due to shrinkage strain (line 7 of Tehran subway), c: chipping (line 3 of Tehran subway), d: improper dowel nut insertion (line 7 of Tehran subway), e: improper finishing (line 3 of Tehran subway), f: imperfect geometry of steel cage (line 3 of Tehran subway), g: hanging socket (line 1 of Tabriz subway), h: honeycombing (line 1 of Tabriz subway)

Here are some clarification for each damage happened during the production:

- **Crack of concrete segments:** Crack in concrete segments is caused by unsuitable mix design and improper conditions of segments curing including shrinkage strain, delayed ettringite formation, carbonation and mistakes by operators, which could be caused by insufficient cooling of concrete segments, and also inappropriate stacking of them. Cracks created due to weak concrete, display minute openings of less than one millimetre wide but the cracks caused by operational errors might rise to one centimetre in width.
- **Chipping of concrete segments:** Chipping in concrete segments might be caused by faulty lubrication of the moulds, inaccurate removing of segments from moulds, and their improper handling in temporary or permanent storehouses. Generally chipping is due to operator's mistake.
- **Improper dowel nut insertion:** Dowel nuts are used at the installation time of the concrete segments in tunnel to reduce probability of damage occurrence. In fact, dowel nuts are placed at designed points to place the concrete, and to accommodate dowels inside them. In case of unsuitable placements or lack of dowel nuts, damaging chance the segments is increased during installation process in the tunnel.
- **Improper finishing:** Formation of air bulbs during segments vibration on the extrados sides is normal. Incomplete smoothing gives an extremely irregular shape to the segments in the side and results in waste of grease from the TBM tail brushes which is very expensive and highly pollutant (Guglielmetti et al., 2008).
- **Absence of hanging sockets:** Hanging sockets are used for holding facilities such as injection hoses, alarming and alerting devices, etc. In the event that these segments aren't fixed to the segments in course of fabrication; the crew responsible for execution of in – tunnel affairs have to drill required holes in concrete segment to accomplish the needed connections and attachments, which in turn, exposes the segments to further harms.
- **Imperfect geometry of steel cage**: When dimensions of the cage made of steel bars do not follow the exact designed patterns, concrete would not dress the bars completely and it leaves the exposed portions for corrosion and rusting after the segment is installed in the tunnel.
- **Honeycombing:** Honeycombs are hollow spaces and cavities where cement fails to fill voids between coarse-aggregate particles. Unsuitable concrete proportions like lack of fine aggregate and cement, low workability, coarse aggregates etc. and faulty placement of concrete like slow placement rate, unsuitable vibrating etc. lead to such a damage. Honeycombing results in more permeability, corrosion of steel reinforcement and lower resistance of the concrete segments.
- **Bleeding:** Disability of the concrete in confining mixing water is called bleeding which comes about an account of improper mix design. As a result of such a damage, weak superficial extrados are created, permeability of precast segments is increased, bond between cement and aggregates and also concrete and reinforcement is reduced, etc. [12, 13].

3. Effects of Damages at Production Stage on Quality of Tunnel Lining

Segments which aren't seriously damaged at production site could obtain required conditions for being transferred to the tunnel, if being repaired effectively. Advised conditions are on the basis of specifications acknowledged by a quality control system which is defined for a special project. If the segments don't achieve the required conditions, they wouldn't be allowed to be used in the tunnel. Segments that don't meet the necessary requirements for being installed in the tunnel are stored somewhere near the tunnel or in the permanent warehouse of the segment factory and later on, they would be used in locations like stations where their linings shall be demolished after TBM have passed through and destruction bases are formed.

Occasionally, the quality control system of the factory is, to some extent, unable to accurately distinguish major, minor or none damaged segments from one another. In this case, and if the damaged segments are carried to the tunnel and installed, the lining might suffer more intense damages due to the forces imposed by TBM's jacks, grout, and ground pressure. Figure 4. illustrates effects of in- factory damages on in-tunnel installed concrete segments.

As it is shown in the Figure 4, all damages which happen to the concrete segments during entire course of the tunnel excavation result in reduced durability of lining system. The weakening also arises due to corrosion in steel bars and reduced strength of concrete in segments. Considering damages occurred in concrete segments in tunnel, one can conclude that damages appeared in these pieces at the construction time of the tunnel could be outlined as crack, chipping and troubled sealing system. Hence, damages which occur in segment factory aggravate the damages that are related to construction stage of tunnel and hence as described earlier, durability of the lining is decreased, accordingly. Figure 5. displays damages at the time of tunnel excavation and Figure (6) shows chipping of concrete segments in production plant and tunnel of Golab water conveyance tunnel.

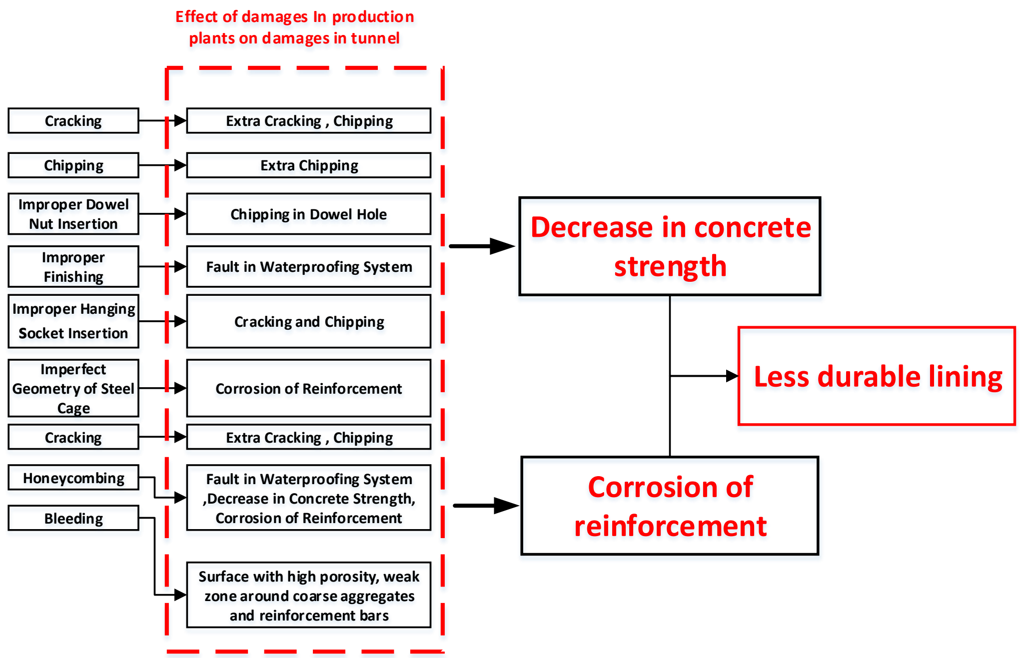


Figure 4. Effects of damages to the concrete segments happened in the production site on tunnel lining

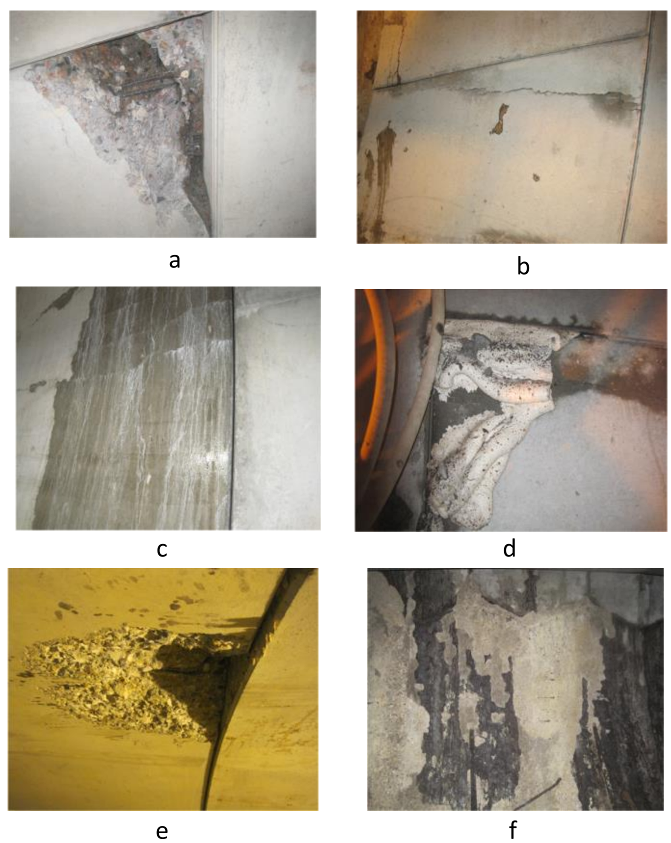


Figure 5. Damages of segments in tunnel, a: chipping (line 7 of Tehran subway), b: crack (line 2 of Mashad subway), c: crack and flow of water into tunnel (line 7 of Tehran subway), d: damage at gasket grooves (line 1 of Tabriz subway), d: damage at dowel insertion hole (line 1 of Tabriz subway), f: corrosion of reinforcement and concrete (Nosood water conveyance tunnel)

Figure 6. Chippinging of concrete segments in Golab's segment production plant and tunnel

4. Chipping and Crack in Concrete Segments

Chipping and crack of concrete segments at production site are among the most important damages applied to these precast concrete segments. Chippings in concrete segments enjoy high importance since they have to be fixed and repaired before delivery to the tunnel. High expenses should be dedicated to fix a considerable sized chipping in a piece, although in most cases it might not be repairable if the chipping of the segment is located in the areas associated with the gasket grooves. Unlike chippings, cracks of the segments at production site could not be repaired due to distribution of them all over the surface of the segments. However, because of minute openings in such kinds of cracks, they are mostly ignored but it should be noted that the cracks of the kind are widened when installed in tunnel due to the effects of the forces imposed by TBM's jacks. As a rule, it is indisputable that both damages on concrete segments make them confront tremendous reduction in durability as linings in tunnels. That is why more studies and inquiries are called for.

4.1. Chippings in Concrete Segments

Chippings of concrete segments could, traditionally, emerge on account of the following circumstances:

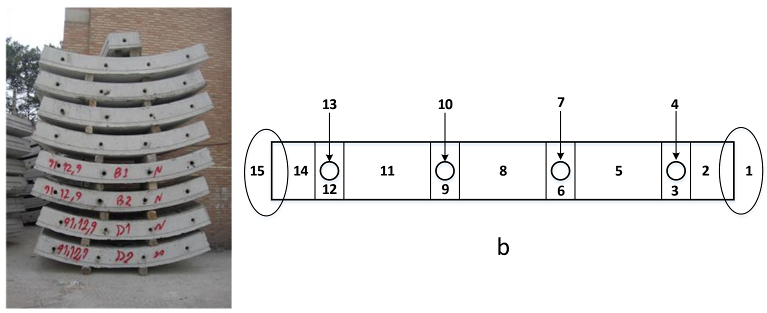
- Deficient lubrication of moulds while casting
- Insufficient resistance of concrete segments when demoulding
- Inappropriate lifter
- Incorrect handling by lift trucks while being carried to temporary or permanent storage area.
- Non – accordant stacking of precast segments in temporary or permanent store house.

Obviously, several other reasons could cause chippings in concrete segments; however, they less probably cause them to occur compared to those mentioned in the above section. Chippings for any of the underlying reasons have its their own characteristics which differ from one to another. It is essential to lubricate the molds in a proper manner before casting the concrete. Improper lubrication would cause sticking of the concrete to metallic mold, and as a result chippings would be inevitable at the detachment of the dried segment from the mold. These kinds of chippings generally occur at the corners or the edges of the concrete segments. Figure 7-a shows chippings on the edges and borders of the concrete segments because of inaccurate lubrication of the molds. The inadequate strength of concrete segments leads to crack of the segments while removing from the molds, but when a wrong kind of lifter is used in the segment factory, chippings may happen at lifter's contact points with the segment. Such kind of chipping is displayed in Figure 7-b and finally chipping, due to improper handling and stacking of the segment, is seen in Figure 7-c.

a b c

Figure 7. Concrete segment damages due to improper a: lubrication b: lifter and c: stacking

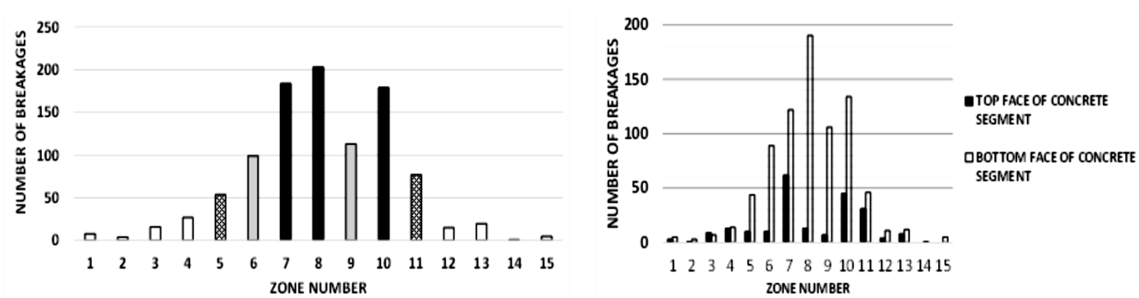
For understanding causes of chippings of concrete segments, a field study was conducted on the segment factory of line 3 of Tehran subway project. This particular fabrication site was chosen because the number of chippings in this location was higher in number in comparison with other types of damages in the production factories. 282 segments of damaged concrete segments in line 3 of Tehran subway were statistically examined. To detect exact locations of chippings, the segments were divided into 15 zones. Figure 8-a shows stacking manner of segments in the warehouse, and Figure 8-b display the zone method.



a

Figure 8. Concrete segments of line 3 subway segment factory a: stacking method b: zone method

Figure 9-a is drawn to show concrete segment's chippings in the zones which are mentioned in Figure 8-b and distinction of amounts of chippings in upper and lower sections is displayed in Figure 9-b.



a b

Figure 9. a: chipping magnitude in each zone b: comparison of chipping magnitude in upper and lower face of concrete segment

Looking at the Figure 9-a, it can be concluded:

- Black columns show maximum magnitude of chippings. These zones are relevant to locations of holes to place dowels and middle parts of the segments. The zones are associated with contacting lifter while demolding the segments.
- Gray columns display noticeable chippings. These types of zones are related to the instance of placing products in permanent storage when contacts shims.
- Hatched columns show intermediate chippings. This class of zones is linked to transferring allotments from provisional storages to long-lasting ones due to hit by lifter's forks.
- Chippings in other zones are potentially overlooked.

Concrete segment's chippings in zones 7, 8 and 10 are developed due to improper lifters and inadequate resistance of the segments while demolding, as well. Lifters used in segment factory of line 3 of Tehran subway, bear some protrusions that intrude into dowel holes at the time of demolding products. In case, the segments are not strong enough around the holes, chippings within the area should be expected. To prevent such harms due to above-mentioned shortcomings, frictional or vacuum lifters, like those utilized in line 1 of Tabriz subway must be used. Also, the initial resistance of the concrete in segments must be promoted. Figures 10-a and 10-b depict lifter used in segment factory of line 3 of Tehran subway and frictional lifter employed for line 1 of Tabriz subway, respectively.

a b

Figure 10. Lifters used in: a: line 3 of Tehran subway b: line 1 of Tabriz subway

Concrete segment's chippings in zones 6 and 9 are due to improper placement of the segments in the permanent warehouse, and those in zones 5 and 11 caused by hitting forks of lifting trucks. Lastly, chipping in unrelated zones could be derived from false lubrication and some miscellaneous non-predictable sources. Considering the fact that most chippings belong to the lower portion of the segments (Figure 9-b) which leads to damaged gasket grooves, thus they need to be repaired prior to moving to the tunnels; however, on many occasions, repairing is not possible and even so, the procedure would dictate a high cost to the project.

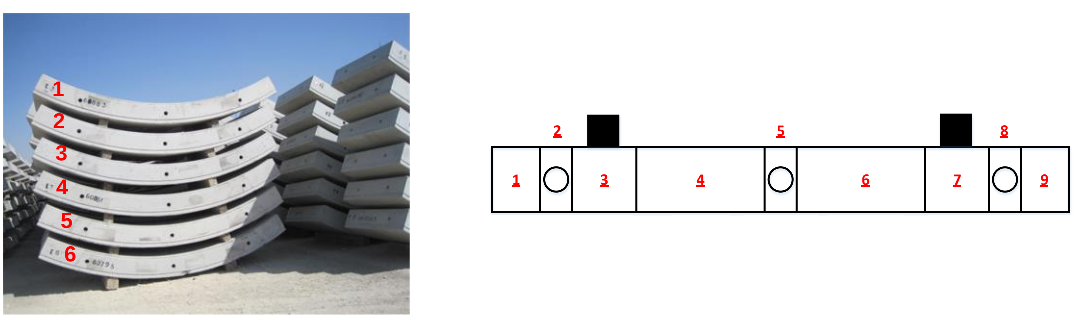
4.2. Crack in concrete segment

Crack in concrete segments have some sources as outlined below:

- Human error (operators' error)
    - Insufficient cooling of segments while demolding in winter.
    - Inappropriate storing in permanent warehouse.
- Crack due to poor mix design and curing of the segments
    - Strain of delayed eteringite formation
    - Shrinkage strain
    - Carbonation

To investigate crack at production site, 342 precast segments from line 7 of Tehran subway were considered under statistical evaluation. Figure 11-a depicts stacking method and 11-b is illustrating the sketch of the zone method.

As it can be inferred from Figure 11-a, concrete segments are classified into 6 statistical populations in accordance with the order in which segments are seated on top of one another.



a b

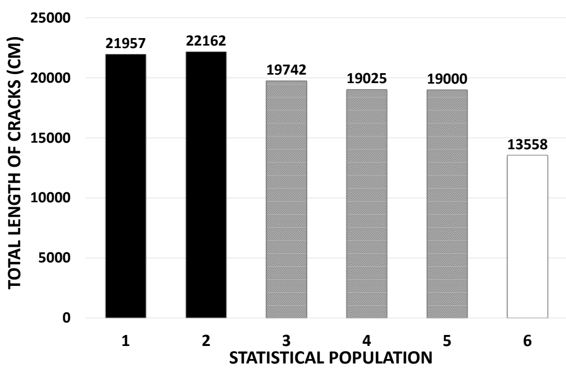
Figure 11. Concrete segments of line 7 of Tehran subway segment factory a: stacking method b: zone method

Concrete segment's crack extent concerning total length, total number and the average length of crack in each of the statistical populations have been demonstrated in diagrams 12-a, 12-c and 12-e, respectively. Considering these diagrams, it is concluded that the statistical population 1 and 2 are the same from judging the total length, number and average crack length perspective. The same outcome is true in regard to statistical populations of 3, 4 and 5. The last performance of the statistical group 6 is not similar to any of the first 5 cases. Statistical groups 1 and 2 have the maximal quantities of crack and statistical groups of 3, 4 and 5 show less numbers of crack compared to groups 1 and 2. So, statistical group 6 has the least magnitude of crack.

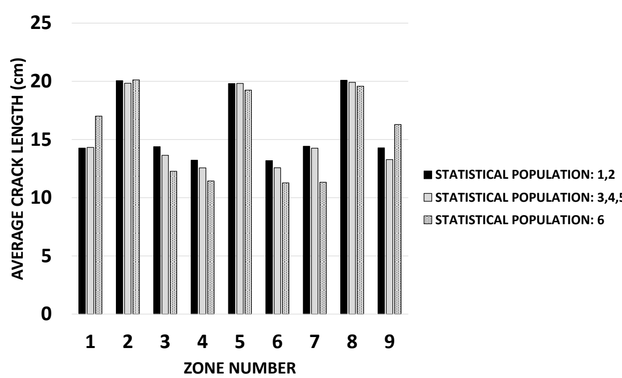
Diagrams 12-b, 12-d and 12-f show extents of cracks in each statistical population in accordance with zone separations which was displayed in sketch 11-b. To obtain better results, the average amounts of crack were figured in these diagrams for statistical populations 1 and 2, and also for 3, 4 and 5. Statistical population 6 was noted, separately.

Considering the diagrams, it can be concluded that the extent of crack of concrete parts in all zones except 1 and 9 in statistical population 1 and 2 are larger than populations 3, 4 and 5 while population 6 contains the least crack. This also could be apprehended through observing the trend shown by the average length of crack. Furthermore, the average extents of crack in zones 2, 5 and 6 which belong to the dowel holes are equal to 20 cm. In other words, if concrete parts crack within these zone, they would grow until they reach the holes. This business is true with all and every statistical population. It should be noted that the thickness of segments used for line 7 of Tehran Subway is 35cm.

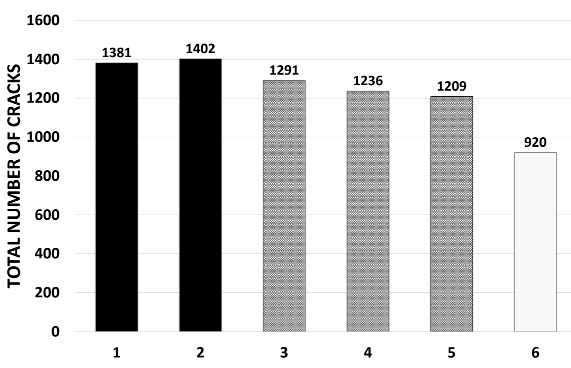
Data collection exercise of cracks identified by concrete segments of line 7 of Tehran subway started in October 2012. At the time, some segments had been produced in April of the same year, therefore they were aged 180 days. Examining these segments, which were amounted to 114 specimens, took one month. In November of the same year, 132 segments of the segments which were fabricated in September and had 60 days old were selected, and finally, 96 concrete segments, with only 28 days of age, were considered for data collection, in December 2012.



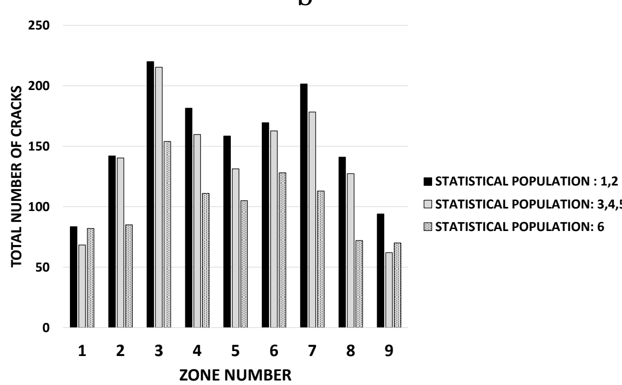
a



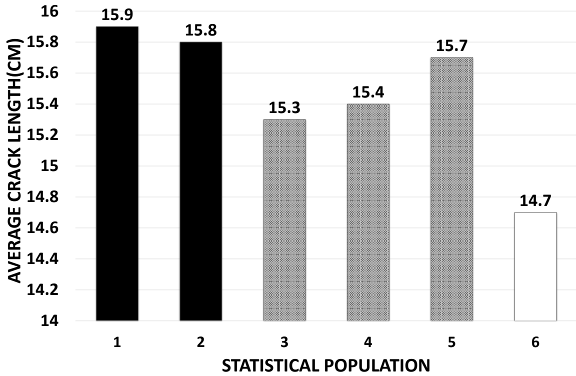
b



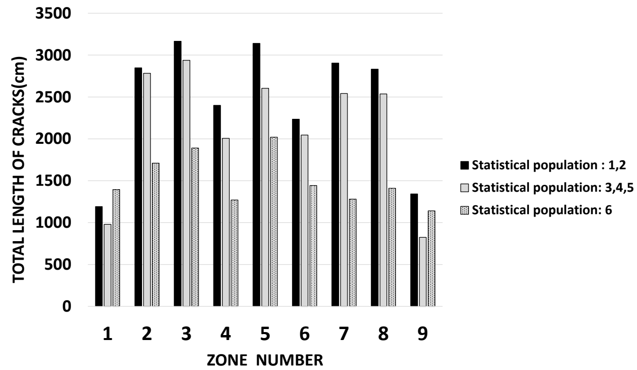
b



d



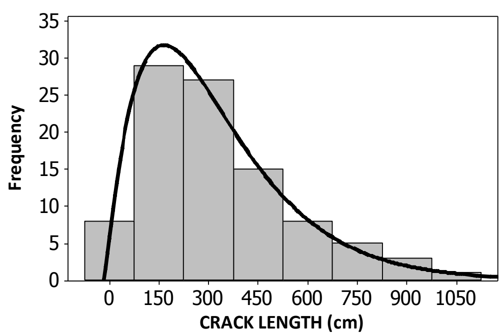
e



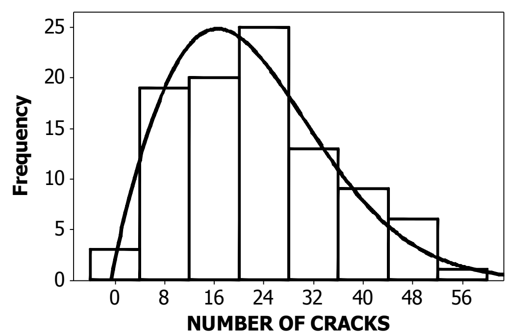
f

Figure 12. Crack magnitude in the statistical populations

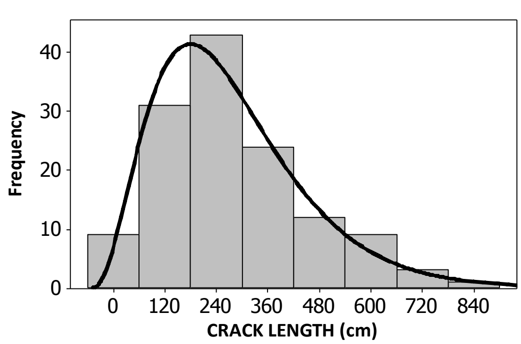
Figures 13-a, 13-c and 13-e show the statistical distribution of crack lengths related to 28, 60 and 180 days aged concrete segments respectively and also Figures 13-b, 13-d and 13-f show the statistical distribution of total number of cracks of the above mentioned age groups, respectively. Diagrams 13-a and 13-b reveal that concrete elements holding total cracks length of 150 cm and total cracks number of 24 are highest in abundance. Focusing on curves 13-c and 13-d, it can be observed that the concrete segments with crack length of 240 cm and number of 19 cracks are more abundant, and finally, curves 13-e and 13-f indicate that, such kind of concrete segments when carry crack with total length of 300 cm and total number of crack cases 32 stand the highest in abundance, compared to other concrete segments used in the tunnels. It is worth mentioning that concerning the segments of 180 days old, cracked allotments with total length of 600 cm show a substantial amount in counts. Taking the above mentioned issues into account, one could conclude that the longer the time between production and gathering exercise of cracks, the more amounts of cracks might appear.



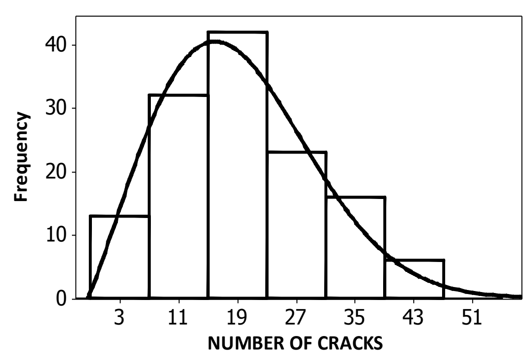
a



b



c



d

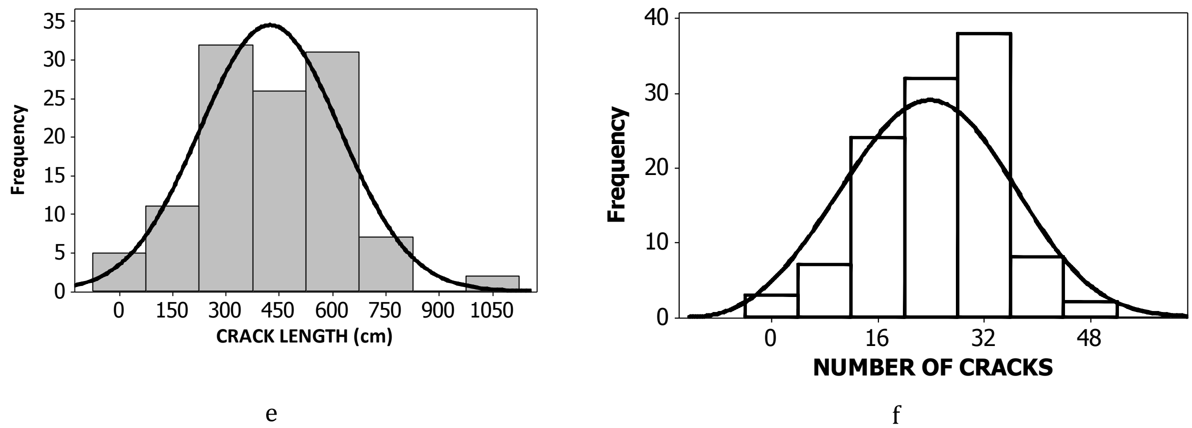


Figure 13. Crack magnitude based on time

According to what was mentioned earlier, it is proved that the cracks in concrete segments are directly related to time dependent behavior, shrinkage strain and the creep, of concrete. As a matter of fact, this is the reason for higher amounts of damages in statistical populations of 1 and 2. The segments included in these populations acquire the most influence from the environmental factors such as wind blow, and sun light, while other statistical populations get less influenced by these factors. It should be, also, noted that the 6th statistical population is under the least environmental effects. Humidity of segments of this group is contributed to the earth humidity, therefore we see less shrinkage strain in this category of segments. So, according to these observations, it is advised that the statistical populations 1 and 2 bear the most, and the 6th bear the least measures of shrinkage strain. This could justify the relationship between cracks in concrete segments of line 7 of Tehran subway, and the crack mechanism.

Zones 1 and 9 do not show similar course as other zones in different statistical populations. These two zones are not influenced by any force except for their own weights, while other zones are under the effect of weights of the segments in which they are placed on top. This phenomenon causes creeping efficacy on cracks happened in these zones. Under conventional circumstances, creeping along with relaxation of the stresses in concrete segments would delay the crack occurrence. This would happen where shrinkage strain develops tensile stress that causes crack in the segment in some lower stresses, less than what is designed based on expected tensile strength at production stage [22].

The segments included in statistical population 6 bear the highest weight force of the segments on the top, hence the major amounts of creeps arise in segments of the population. On the other hand, based on previously given details, the least measure of shrinkage strain come about in the population. The phenomenon is true with the concrete segments of populations 1 and 2 except for one case, that is, this group of segments concedes the highest amount of shrinkage strain and the lowest magnitude of creeping. Above mentioned explanations justify the procedure of concrete segment crack of the statistical populations of 1 - 6. Zones 1 and 9 which are not influenced by the weight of upper segments in none of the statistical populations, show different types of conducts in crack compared to other zones. The phenomenon attests the importance of creeping in crack. At length, mechanism of crack of concrete segments in line 7 of Tehran subway is a combination of influencing force and shrinkage strain, resulting in decreased crack of segments in statistical populations of 1-6.

5. Reason of Damaging the Concrete Segments During Production and Transportation and Pre-Emptive Method for Prevention

Table 1. describes causes for damages in the concrete segments at production site, transportation stage, and prevention policies. Focusing on the table it can be concluded that damages are related to unsuitable concrete which can be cut down by correcting the mix design, curing condition and concreting and damages that initially were as a result of human error, they all can be corrected through proper training of the operators.

In general, it could be claimed that the damages resulted from the operator's errors and unsuitable concrete need further studies to recognize and stop them.

As a rule, to prevent damages imposed to concrete segments, following four steps must take:

- Designing an efficient quality control system in accordance with the conditions under which the project is being executed in a way that it enables separation of:
  - Concrete segments eligible to be carried to the tunnel
  - Repairable segments
  - Non-repairable segments
- Well training along with close control of the operators of each and every department or section without replacing or shifting them unless for a justified reason.
- Presenting suitable mix design and curing besides enough and precise testing and trial every time concreting is performed.

Employing standard and up to date equipment in all and every stage of production as well as transporting the segments.

Table 1. Types of potential damages to concrete segments, their reasons and the ways of preventing their occurrence

Stage the damage occurs	Nature of damage		Reason	Preventing
Damages at production facility	Damage due to improper concrete	Bleeding	Unsuitable mix design and concreting conditions	Using fine grain cement. Using cements of high alkaline, or adding calcium chloride. Reducing amount of water when mixing the concrete.
		Honey combing	Excess slump of concrete, low amount of cement in concrete, substantial difference in characteristics of aggregates, decreased amounts of fine components, excessive usage of lubricants, not using bubble creating materials, unfit vibrator, wrong moulds, non-acceptable concreting.	Mix design and concreting should be done in a manner to recover the measures mentioned in the column which describes damages.
		Crack	Strains due to shrinkage , carbonation and delayed eteringite formation	Mix design and curing circumstances must be in a manner to produce the least amount shrinkage strain. Curing temperature when using steam shouldn't exceed 75 c.
	Damage due to operator's errors	Crack	Inadequate cooling of segments when demolding. Wrong placement of shims in between segments in permanent warehouse.	Leaving the segment indoor for at least a day and also blanketing them especially in cold seasons. Placing shims aligned, or at least with minimum deviation from the straight line
		Improper dowel nut insertion	Operator's error	Promoting the Operator's trainings
		Chipping	Operator's error	Being cautious while transporting segments from moulding area to temporary and then permanent storages. Careful lubrication of moulds. Using frictional lifters.
		Imperfect geometry of steel cage	Fault in steel cage's template. Excess tolerance in moulds.	Promoting the Operator's trainings
		Imperfect finishing	Operator's error	Promoting the Operator's trainings
		Missing of hanging socket	Operator's error	Promoting the Operator's trainings
Damage at the transportation stage	Chipping and crack		Operator's error	Promoting the Operator's training and employing standard machineries to carry concrete segments.

6. Conclusion

All concerns discussed and presented in this investigation are based on experiences with mechanized tunnel boring projects in Iran and extensive study of the related reports. Outcomes of investigating damages in the concrete segments in the production site and transportation stage could be addressed as below:

- Damages sustained by concrete segments at production site and at transferring to the tunnel would be due to improper mix design and curing and also by errors from the operators' side.
- In case of lack of a suitable quality control system, the damaged segments in the construction or transportation stages would be used as lining in the tunnel. Obviously vulnerability of this kind of segments is higher than those which are intact because the forces applied to them in the time of installation and utilization affects them more than they affect intact segments.
- Final effect of damaged concrete segments on all stages of founding a tunnel is weakening the lining function of the segments, which itself arises through erosion and rusting of the steel bars and followed by reduction of the strength of the concrete.
- Operator's errors as well as unsuitable equipment are the most important reasons for segment's chippings.
- Curing the concrete which is directly related to mix design is the main reason for crack.
- The main reasons for chipping in the factory are using improper lifters, improper warehousing in permanent storage and wrong methods of carrying segments on lift trucks.
- Considering the fact that the bottom of the concrete segments gets more damages in comparison to upper ones, in most cases repairing them is practically impossible.
- Crack mechanism of segments at production site is because of shrinkage strain and creeping of the concrete of segments.
- Using precise quality control system, operator's training, not replacing the operators of different sections with one another, employing standard tools and equipment and also presenting accurate mix design and curing along with adequate tests and trials at concreting stage are all parts of a guideline that by following them there would be a good amount of damage reduction in the stages of production and transportation.
- The bottom line is that the cost of prevention of damages is always lower than the cost of repairing.

7. References

[1] V. Guglielmetti, P. Grasso, A. Mahtab, S. Xu, Mechanized tunnelling in urban areas: design methodology and construction control, CRC Press, 2008.

[2] AFTES, Association Française des Tunnels et de l'Espace Souterrain, France, 1997.

[3] S. Mitsutaka, Causes of shield segment damages during construction, International Symposium on Underground Excavation and Tunnelling, (2006).

[4] C.B.M. Blom, "Design philosophy of concrete linings for tunnels in soft soils", (2002).

[5] S. Cavalaro, C. Blom, J. Walraven, A. Aguado, "Structural analysis of contact deficiencies in segmented lining", Tunnelling and Underground Space Technology, 26 (2011) 734-749.

[6] J.-s. Chen, H.-h. Mo, "Study on effect of segments erection tolerance and wedge-shaped segment on segment ring in shield tunnel", Journal of Zhejiang University-SCIENCE A, 7 (2006) 1864-1869.

[7] J. Chen, H. Mo, "Numerical study on crack problems in segments of shield tunnel using finite element method", Tunnelling and underground space technology, 24 (2009) 91-102.

[8] H. Mo, J. Chen, "Study on inner force and dislocation of segments caused by shield machine attitude", Tunnelling and underground space technology, 23 (2008) 281-291.

[9] J.H. Georg, K. Davorin, Selection of segmental lining system and repair classification, Proceedings of the CSSE Symposium DAMOCS. Dubrovnik, (2004).

[10] F. Gruebl, Segmental rings (critical loads and damage prevention), International Symposium on Underground

Excavation and Tunnelling, Bangkok, Thailand, (2006).

[11] W.G. No, I.T. Association, "Guidelines for the design of shield tunnel lining", Tunnelling and Underground Space Technology, 15 (2000): 303-331.

[12] J. Hanson, Optimum steam curing procedure in precasting plants, Journal Proceedings, (1963).

[13] S. Mindess, J.F. Young, D. Darwin, Concrete, Prentice Hall, 2003.

[14] M.D. Crespo, C. Molins, A.R. Marí, "Effect of variations in thermal-curing cycle on the cracking risk of precast segmental tunnel lining", Construction and Building Materials, 49 (2013): 201-213.

[15] AASHTO, A.A.o.S.H.a.T. O., Washington DC, 2000.

[16] A.C. 517, Accelerated Curing of Concrete at Atmospheric Pressure: State of the Art, American Concrete Institute, 1992.

[17] PCI, Accelerated curing of concrete at atmospheric pressure –State of the art., (1980).

[18] A. Herrenknecht, K. Bäppler, Segmental concrete lining design and installation, Soft Ground and Hard Rock Mechanical Tunneling Technology Seminar, (2003).

[19] D. Kolic, A. Mayerhofer, "Segmental lining tolerances and imperfections", Google Scholar, 8 (2011).

[20] C. Herrenkenect, Tehran Metro Project - line 3, (2006).

[21] C. Selli, Tehran Metro Project - line 7 North-South section, (2008).

[22] P.K. Mehta, Concrete. Structure, properties and materials, McGraw-Hill Publishing, 1986.