Cracking of Open Traffic Rigid Pavement

by Chatarina Niken

Cracking of open traffic rigid pavement

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Abstract. The research is done by observing the growth of real structure cracking in Natar, Lampung, Indonesia compared to C. Niken's et al research and literature study. The rigid pavement was done with open traffic system. There are two main crack types on Natar rigid pavement: cracks cross the road, and cracks spreads on rigid pavement surface. The observation of cracks was analyzed by analyzing material, casting, curing, loading and shrinkage mechanism. The relationship between these analysis and shrinkage mechanism was studied in concrete micro structure. Open traffic make hydration process occur under vibration; therefore, fresh concrete was compressed and tensioned alternately since beginning. High temperature together with compression, cement dissociation, the growth of Ca^{2+} at very early age leads abnormal swelling. No prevention from outside water movement leads hydration process occur with limited water which caused spreads fine cracks. Limited water improves shrinkage and plastic phase becomes shorter; therefore, rigid pavement can't accommodate the abnormal swelling and shrinking alternately and creates the spread of cracks. Discontinuing casting the concrete makes both mix under different condition, the first is shrink and the second is swell and creates weak line on the border; so, the cracks appear as cracks across the road.

1 Introduction

Rigid pavements generally are made from concrete, with or without reinforcement. Rigid pavement lays over sub base and sub grade as shown in Figure 1. Sub base can be made from lean concrete or stone structure. Over the past few years, the reliance has shifted more to rigid pavement because of its low maintenance cost, long service life, and smoother riding surface [1]. Besides its of the advantages, rigid pavement is expensive due to the high cost of concrete and reinforcement. The economic consideration are carried out for the pavement design of a section by using the results obtained by design methods and their corresponding component layer thickness [2]. Because of low initial cost, flexible roads are preferred to concrete road pavement, but bituminous roads deteriorate during the rainy season and maintenance becomes costly [3]. In concrete pavement, a single concrete mixture design and structural surface layer are selected to resist mechanical loading without an attempt to affect pavement shrinkage, ride quality or noise attenuation adversely [4]. It is important to prevent water evaporation right after casting because micro cracks of rigid pavement can avoided. The micro cracks can grow and accumulate due to applied load and by climate. The accumulation of cracks can create deterioration in the concrete; therefore, rigid pavement performance is decreased and its service life becomes shorter. These circumstances can change into serious problems because accumulated cracks make the structure unsafe. Rigid pavement or concrete pavement needs high attention during planning, preparing, placing, curing and load scheduling. The faults in every step of producing rigid pavement leads to concrete deterioration, micro cracks and wider cracks.

There are many types of cracks such as the tearing of concrete through paver, plastic shrinkage cracking at pavement surface, map cracking (craze cracks), transfer and oblique cracks within the panel, random longitudinal cracks within the panel, corner cracks (break at panel corner), random transverse cracks at or near transverse joints, random longitudinal cracks at or near longitudinal joints, and cracks in front of saw during joint cutting [5]. Variation of crack width in Texas was studied [6]. They mentioned that an immediate decrease in crack width was observed after rain. There was clear evidence that moisture variation in concrete has substantial effect on concrete volume change and crack widths [6]. Locally calibrate the transfer cracking and IRI (smoothness) performance model for newly constructed and rehabilitated rigid pavement has been published [7].

Cracks are also caused by flexural fatigue, and non-homogenous deflection in sub-base or sub grade. The non-homogenous deflection has been led by erosion of the sub-base or sub-grade. Erosion of the sub-base occurs if it is structural stone; thus, this erosion is not similar in every point in the sub-base. Non-homogenous erosion makes deflection different at any point of rigid pavement. The swelling of roadbed soil also causes deformation of its upper layer [8]. Erosion and flexural crack types, generally begin from the bottom to the top, and crack by swelling of roadbed soil begin from the top. Top-down cracking has been found to be a predominant mode of asphalt pavement distress in Florida [9]. Deflection, erosion, and swelling always occur because of climate change; so, the base layer of rigid pavement

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has dynamic properties. Field observation has demonstrated that there is an increase in reflecting cracking of PCC (Portland Cement Composites) slabs placed over relatively a stiff base layer [10].

Foundation layers in finite element analysis of jointed pavement concrete system were done with appropriate idealization to predict the thermo mechanical response of jointed PCC slabs accurately [10]. Many researchers have also studied rigid pavement response using the finite element method [11-13]. Significant changes in the slab curvature shape (curl/warp) also occurs through thermal gradient, from positive to negative and vice versa. Even, critical cases in the stress were found in the combination of wheel load and the positive thermal gradient [14-17]. Statements as mentioned above lead particles movement to any direction. The horizontal movement of any point is almost uniform, but transverse movements are different [18].

From the above mentioned, it can be seen that there are complex mechanisms which cause deformation due to induced cracks such as the raw materials of concrete, mix design, casting system, treatment right after casting, curing system, loading time, loading system, fatigue, weather, erosion in sub-base/sub grade, and swelling of roadbed soil. Therefore, the study of cracking rigid pavement can involve a very wide field. The objective of this study is to understand the cause of rigid pavement cracking which occurs in Natar, Lampung Province, Indonesia.

2 Experimental details

The experimental details were divided into 2 parts: Natar, Lampung, Indonesia rigid pavement and Niken, Elly, and Supartono's research of rigid pavement (un-published).

The research was done through a case study in one place in Natar Lampung Province, Indonesia. The research was done by observing cracks which appeared in Natar. The observation included the age of lean concrete (LC) as sub-base and rigid pavement when the cracks appeared, the growth of cracks, crack width, quality of concrete, treatment right after casting, curing system, weather, and loading system. The rigid pavement was built with open traffic system: half part was done longitudinally, while another part was used as traffic.

Rigid pavement in Natar uses concrete quality of 30 MPa. The rigid pavement (RP) lays over the lean concrete (LC) with a compressive force (fc') of 15 MPa. Rigid pavement in Natar was build with the cross section as shown in Figure 1.

The embankment in Fig.1 is similar to roadbed soil according to AASHTO 1993. The lean concrete function is to obtain homogenous support for rigid pavement and also for rigid pavement plate work. There is no permeable sheet in the base and all sides of the lean concrete and rigid pavement. Right after casting, the lean concrete and rigid pavement were un-covered resulting in contact between the surface of lean concrete or rigid pavement and the surrounding weather occurred.

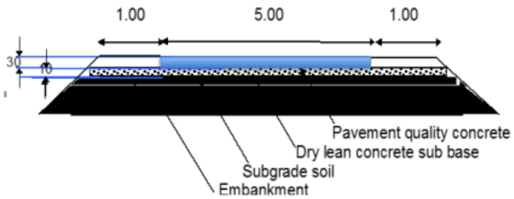

Fig.1. Cross section of the rigid pavement

Curing was done by wet sacks which were sprayed with water 3 times daily without de-molding the side part of both concrete layers. These sacks covered the plate surface for 1 until 7 days. Because of the lack of understanding and control, the sacks were not always wet during curing time. After that, the pavement came into direct contacts with the surrounding weather. The rigid pavement was cast when the lean concrete was 2 days of age.

3 Observation results

3.1 Natar Lampung Indonesia Rigid Pavement

When the lean concrete and rigid pavement was at the age of 1 day, many fine cracks appeared on the surface and all sides of the both. After side molds were released, there also were many cracks in the side part of the lean concrete and rigid pavement and some of them showed more crack width than general fine cracks (Fig.2).

Fig. 2. Fine cracks over the surface of rigid pavement

Fig. 3. Single crack lying a cross the rigid pavement with fine cracks

Figure 3 and 4, show crack that is a single crack a cross the road. The crack divided the road into two parts. Besides the main crack, there are many fine cracks in the lean concrete and rigid pavement layer as shown in Fig.3 and 4.

Fig. 4. Single cracks with chain

3.2 Niken's et al research

There search of Niken et alwhich wereused a full scale plate (3m x 2m) with 130mm thickness to observe deformation behavior of plates.Analysis also involved the change of weather. Indonesian weather was observed over 3 years from November 2009 until December 2011 in Jakarta, Indonesia as shown in Fig. 5 and 6 [19].

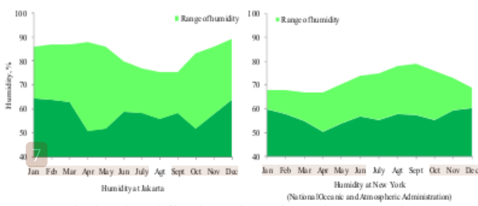

Fig 5. Relative humidity in Indonesia and NewYork

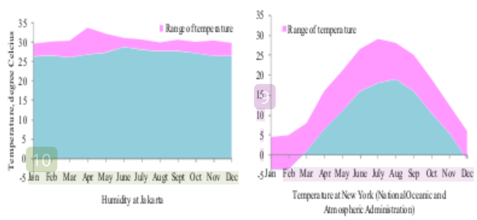

Fig 6. Temperature in Indonesia and New York

The difference between maximum and minimum humidity is about 25% (Fig. 5), while the temperature in Indonesia is always high throughout the year (Fig. 6). This research also used high range water reducer and silica fume. The compression strength of plate is 60 MPa. The concrete quality of Niken'*set al* research was high performance concrete (HPC); thus limited water and much OPC (ordinary Portland cement) were used (Table 1). The mix design of Niken et al's research, and Natar rigid pavement is displayed in Table 1.

The water to cementitious ratio (w/cm) is 0.264 (Table 1). To obtain the accuracy of w/c, HRWR/c, and w/cm, an electric scale was used. Coarse and fine aggregate are under saturated surface condition (SSD). Right after casting, the plate is covered with styrofoam to eliminate water evaporation. After the mold are removed, wet cure is done carefully for 1 to 7 days using sacks by continual monitoring and spreading water on sacks which are beginning to dry. Deformation and concrete temperature are obtained from the vibrating wire embedded strain gauge(VWESG). The VWESG has the ability to detect the strain up to 3000 με with an accuracy of about 0.025% and concrete temperature between -80°C and 60°C with about 0.5% accuracy. Observation was performed righ after pouring with the following schedule: 0-24 hours, every 15 minutes; 24-48 hours, every 60 minutes; days 3-7, every 2 hours; and one time each day using a read out.

Table 1. Material composition

Material	Natar LC (kg/m^3)	Natar RP (kg/m^3)	C Niken (kg/m^3)
OPC	280	380	500
Silica fume	0	0	40
Coarse aggregate	1067	1059	935
Fine aggregate	819	754	800
HRWR	1.12	1.52	7.6
Water	187	183	142.6
w/c	0.668	0.482	0.285
HRWR/c	0.4%	0.4%	1.52%

w/c : water to cement ratio
HRWR/c : HRWR to cement ratio

Crack observations wereperformed using a loop 50 times larger displayed in Fig.7.

Fig. 7. Surface of concrete plates in C. Niken's et al research

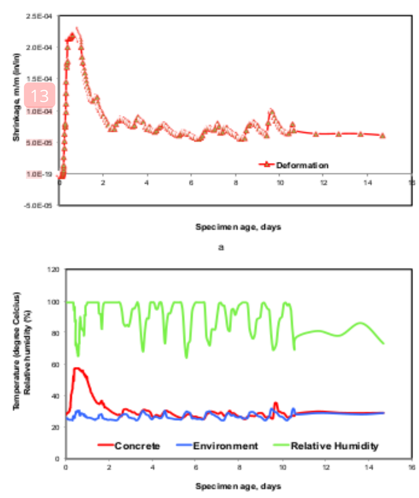

Fig. 8. Deformation of HPC rigid pavement, concrete and environmental temperature and relative humidity

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No cracks were found on the surface and the side of the rigid pavement although limited water was used. The relationship between deformation and time, relative humidity, environment and concrete temperature during observation are displayed in Fig. 8.

Although the concrete quality of Natar is different, the relationship between the two types is available, such as the relationship between deformation and the age of concrete, relative humidity, environment and concrete temperature (Fig.8). By using supporting literature study, the cause of cracks could be obtained.

4 Discussion

Natar rigid pavement cracks occur 1 day after casting and before applied loads. Because there is no preventive mechanism to handle water movement outside the rigid pavement, environment in the surrounding weather completely influences the inner process of rigid pavement since the beginning. Therefore, the internal concrete mechanism together with the influence of the surrounding weather and open traffic as a unity is one factor. The first process is solution. This process is a transition from fresh concrete to hard concrete. In this phase the repulsive/dispersion force is dominating which makes the volume swell. Together with this process, the hydration process is also beginning. The hydration process is a chemical reaction, and in every chemical reaction, there is a change in heat, volume, and adhesive power. Chemical reaction results in free energy which causes particles to move [20]. This energy change is caused by pure thermal processes. The increase of heat is the evidence of an increase in chemical reaction;therefore, the hydration process occurs since casting (Fig.8).

The open traffic system makes the hydration process occur under vibration. Vibration makes the hydration process under compression and the tension condition alternately. Vibration makes coarse aggregate down to the bottom; this action inflicts compression. At the same time high temperature occurs in the concrete. The combination of compression and high temperature make volume swell abnormally [21]. In the tense condition, volume may shrink. A long-term plastic phase of fresh concrete was needed to accommodate both conditions which occur with high fluctuation according to the traffic. This condition could not be met because of the reasons below.

Vibration causes coarse aggregate to be placed at the bottom; hence, matrix becomes filled at the upper part of the rigid pavement, so that most of the hydration process occurs at the area. Plate has a surface which is more spacious than beam or column, without covering this surface, the influence of the surrounding weather is larger. It is clear that the top of rigid pavement is more sensitive to crack than the deeper part.

The hydration process consumes internal water; thus, it can be approached as progressive conversion of free water in the capillary pores to structural water in the solid hydration product. All hydration products contain chemically bonded water. Free water influences ionic transportation, and shrinkage. The condition in which there are no outside influences is called autogenous. No outside influence is needed, so that the amount of calculated water for the hydration process has not changed. Autogenous deformation is a change of volume purely through inner processes occurring right after casting. The maximum rate of autogenous deformation happens during the first 3-12 hours. Limited water causes increasing autogenous shrinkage. Autogenous shrinkage can be more than drying shrinkage [22]. Concrete temperature at this phase can reach 55^{o} C, at the age less than 1 hour (Fig. 8). Until the age of 2 days concrete temperature is higher than the surrounding temperature (Fig.8).

At this critical condition, Natar rigid pavement and lean concrete have no prevention from outside influences right after casting. Casting was done at day time; therefore, outside temperature is high and inside of concrete temperature is also high. Mosa *et al*, 2015, was explains that all crack types are caused by temperature [5].

Internal water which was needed for the hydration process moved outside rigid pavement; in addition to this, high temperature of concrete leads inner water to evaporate; thus, the hydration process occurs with water shortage. High temperature of the surrounding area leads surface water to evaporate. The large surface area makes much water evaporation.

Tension caused by vibration also increases the early shrinkage. At this age, capillary pores was dominating. Until the age of 14 days, the number of concrete pores decreases significantly (Fig.9). Pores with 10-20 cm in diameter in the C-S-H cluster are available [23]. These pores are medium capillary pores. Water in these pores can evaporate even in high humidity such as Lampung, Indonesia, as this water has strong menisci.

Strong menisci make capillary pores and surface forces increase. The plate surface area is larger than another; thus, surface force is also larger. Internal water decreases again because of this force. All these things cause early shrinkage to increases very rapidly.

The loss of water as mentioned above causes the loss of plasticity of rigid pavement also to occur very rapidly. The loss of plasticity is not accompanied with strong particles bond because silica bridges have not formed. Plastic losses and weak bond causes matrix unable to accommodate the change of abnormal swelling and shrinking ; as a result, the particles bonds break and cracks occur. Because top area is more sensitive than the deeper, a lot of fine cracks spread over the surface appear immediately as shown in Fig.2.

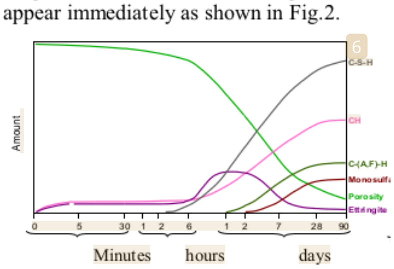

Fig 9. Product hydration rate [24]

Lacking of water at the early stages, can cause delayed ettringite formation or DEF. Ettringite formation causes expansion. If the ettringite formation happens during the plastic phase, expanded space becomes available automatically, but if the ettringite is formed at the beginning or during the hardening of the rigid pavement, deterioration will occur. Inner sulfat attacks concrete or the rigid pavement [25]. The deterioration of concrete will accelerate the growth of existing cracks.

Besides stresses as mentioned above, there are also product hydration forces, and disjoining pressure forces, caused by hidden water in the concrete. Product hydration force will increase according to the product hydration rate (Fig.9). All of stress in microstructure is called microprestress [26]. All stresses both at the level of microstructure and outside influences, such as vibration or surrounding weather should be accommodated by the rigid pavement.

Accumulation of all stresses will break the weakest of bonds and the stress vines and breaks other weak bonds. The position of the weak bond depends on the casting system. Casting of Natar rigid pavement was done from the end of the cross section of road to another end. Waiting time more than 1 hour (depending on the traffic weight) to the next casting makes the concrete character has a significant difference. The more weight traffic, the more compression on the fresh concrete, and the larger the abnormal swelling becomes. The difference is the first casting in the shrinkage phase, while the next casting is in abnormal swelling. The difference makes the connection line becomes weaker than another part. Cracks appear as a single line as shown in Fig.3.

New rigid pavement is cast over lean concrete at the lean concrete age of 2 days; therefore, lean concrete cracks have been growing. The cracks penetrate the young concrete of the rigid pavement, and the rigid pavement becomes cracked. The penetrate force from lean concrete is increases because of the increases of product hydration growth, capillary force, disjoining pressure and also vibration force. The similar forces also occur in rigid pavement. All of the forces hit the relative stiff layer (lean concrete); hence, the forces will be reflected. The reflected force will improve the breaking bond and cracks occur more and more. The circumstances are in accordance with the observation of Ashtiani *et al*, 2016 as mentioned above. To avoid these cracks, the new layer should be cast when the rate of the hydration product is low. According to Fig.9, the rate of product hydration growth declines at the age of 7 days. Besides this, to eliminate reflecting forces, the reflective layer damping force can be retrofitted. Rigid pavement or lean concrete length and width should also be restricted in order that the shrinkage over the width can still be handled.

Surrounding humidity is accompanied by concrete deformation until the concrete age is 11 days. The rhythm of deformation is inverted with the rhythm of humidity even in curing conditions. The highest deformation occurs at the lowest humidity. The peak of deformation occurs when the humidity is the lowest (Fig.8).

5 Conclusion

Based on field observations, in comparison to the research of C. Niken's*et al*, rigid pavement cracks have been studied. The causes of open traffic rigid pavement cracks are:

a. Vibration by open traffic causes coarse aggregate to move down, and concrete matrix fills in the upper part of rigid pavement, as surface stress becomes larger.
b. Vibration makes the hydration process occur under compression and tension alternately.
c. High temperature at the early hydration process together with compression leads to concrete swelling abnormally.
d. The absence of prevention from outside water movement makes the hydration process occur with limited water, and early shrinkage increases.
e. The long time plastic phase is needed to accomodate the both conditions.
f. Lacking of water at early age shortens plastic time; therefore, it can not accomodate the alternate of abnormal swelling and shrinking.
g. Product hydration bonds are not strong enough to sustain accumulated stresses, such as compression, tension, microprestress, and the influence of surrounding weather.
h. The bonds cracks and the stress continue to vine and breaks other weak bonds.
i. Discontinuing casting the concrete makes both mixes under different conditions: the first is shrink and the second is swell. This condition creates a weak line on the border of the second mix; thus, the cracks appear as a single crack a cross the road.
j. The lack of water by the absence of prevention for moving water inside the rigid pavement, high concrete temperature,high surrounding temperature, and delayed ettringite formation makes spread fine cracks appear over the surface of concrete.
k. Microprestress and stress from outside concrete such as vibration, and surrounding weather could be reflected by the refative base layer and penetrate the rigid pavement, and cracks occur more

Suggestions:

To avoid cracks, the suggestions are:

1. Materials conditions are similar to the mix design condition.
2. Sub grade/sub base should in stable condition.
3. If the sub base/ sub grade is lean concrete, lean concrete should free of cracks. If the lean concrete cracks, it is necessary to recover the cracks before casting the rigid pavement.
4. Lean concrete should be strong enough to sustain the rigid pavement.
5. Surrounding weather with high humidity (evening) is better time to cast.
6. All of molds should be covered with an impermeable sheet.
7. Planning of cast should consider: material and equipment readiness, anticipation in change of

weather and location of discharge casting. Casting should be done continuously.
8. Cover all of surface right after casting by an impermeable sheet.
9. Cover all of surface right after casting by an impermeable sheet and wet sacks if the rigid pavement is cast with the open traffic system.
10. Cover the stiff base layer with a damper sheet.

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