Crack Mechanism of Different Concrete Grades under Compressive Loading: Application in Rigid Pavement

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Abstract- The growth of cracks in concretes under different loadings in various structures and their consequent diminishing effect on the lifespan of structures is an age long structural problem. This research investigates the influence of compressive loading on the crack mechanism of different concrete grades 1: $1\frac{1}{2}$: 3 (M_{20}), 1: 2: 4 (M_{15}) and 1: 3: 6 (M_{10}) using three brands of cements available in Nigeria namely Dangote (Type A), Elephant (Type B) and Bua (Type C). Particle Size Distribution (PSD), Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV) was carried out on aggregates in accordance with relevant codes while; compressive test were performed on the hardened concrete while, the crack width was measured using microscopic technique. A coefficient of uniformity (Cu) of 4.00, AIV of 46 % and an ACV of 47.7 % were obtained for the aggregate which are suitable for rigid pavements construction. Maximum compressive strength value of 24.96 N/mm^2, 24.67 N/mm^2 and 24.89 N/mm^2 respectively was obtained for concrete M20 for Type A, Type B and Type C cement at the 28 day. A corresponding crack width of 0.97 mm, 0.89 mm and 0.93 mm was obtained while; a yield period of 57.66 sec, 58.33 sec and 53.33 was obtained respectively. Comparing with the International Organization for Standardization, concrete grade M_{20} any of the cement types is suitable for the construction of rigid pavements with heavy traffic volume while M_{15} is recommended for low traffic volume.

Keywords: Concrete Grades, Compressive Loading, Cracks Mechanism, Rigid Pavement, Traffic Volume
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1 Introduction

Concrete is a composite material composed mainly of water, aggregate, and cement. Often, additives and reinforcements are included in the mixture to achieve the desired physical properties of the finished material. It is the most versatile and most widely used construction material worldwide which, can be engineered to satisfy a wide range of performance specifications. According to Neville and Brooks (2010), the most used materials in construction are concrete and steel. However, more attention is needed on the properties of concrete as its mode of production differs from site to site.

Concretes can be classified as low grade, medium grade and high grade with a compressive strength of 15 N/m^2, between 16 to 50 N/m^2, and between 51 to 100 N/m^2 at 28 days respectively; while a compressive strength beyond 100 N/m^2 is regarded as ultra- high strength concretes (Mahzuz et al., 2011). However, the strength of concrete mainly depends on the amount of water used, aggregate gradation, and aggregate size and shape, cement quality, mixing time, mixing ratios, and curing among others etc. (Kabir, 2006). According to Ryan (2010), concrete is strong in compression and weak under tension; nevertheless, it has been observed that concretes crack under compressive loading. This led several researches to work on methods of improving its strength, basically, the stress-strain characteristics of concrete. Crack/fracture mechanism encompasses fracture initiation and propagation, many concrete structures fail due to cracks, and it is essential to realize the significance of the fracture in real life situation to avoid failure. Hence, this research investigate crack mechanism of different concrete grades under compressive loading and its application in rigid pavement.

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2 LITERATURE REVIEW

Concrete, an economical material widely used in civil engineering works is of high relevance as it is not susceptible to rot, corrosion or decay as other building materials do. It can be molded into almost any desired shape and has resistance to fire, wind, and water among others.. The strength and durability of concrete are classified according to different grades which depend on the water-cement ratio and other parameters including; mix ratios, curing age and conditions among others. According to Syed et al. (2014), concrete encompasses certain type of cracks in pre-hardening stage and therefore develops some other types of cracks in post hardening stage in life of structure due to various reasons, even with extreme care in prevention of cracks.

They concluded that “Cracks can be treated as cancer in reinforced concrete structure, as cancer which in its primary stage is curable to a certain extent but becomes danger to life in later stage; same happens with cracks”.. Cracking is an essential feature of the behavior of concrete structures. Even under service loads, concrete structures are normally full of cracks. Failure of concrete structures typically involves the stable growth of large cracking zones and formation of large fractures before maximum load is reached (Bažant, 1992). Cracks are faults in structural elements which affect the structural integrity, aesthetics or both in a structure. The mechanics of this fault known as crack mechanism is the relationship between the stress and strain behavior of homogenous, brittle materials (Neville and Brooks, 2010). Concrete is brittle but not homogenous due to the differing properties of its constituents, hence, it is referred to as a quasi-brittle material. Shah et al. (1995) showed that the stress-strain curve is always linearly elastic up to the maximum stress for an ideally brittle material. They argued that for a quasi-brittle material like concrete, there is significant non-linearity before the maximum stress. Strain softening can be observed under stable propagation of crack. They also postulated that if a closed loop displacement controlled test machine is used, both opening of the crack and unloading of specimen can be observed for post peak part of the stress-strain curve. Fracture mechanics assumes that an initial fracture begins its growth at the proportional limit, and then keeps propagating in a stable manner until the peak stress, so much that a new cracked surface is formed by extension of cracks (Wang and Shrive, 1995). According to Anderson (2005), there are two main causes of failure in structures:

i. negligence during design, construction, or operation of structures,
ii. application of a new design or material, which produces unexpected results"

In another research by Bažant (1992), he opined that fracture mechanics is a failure theory approaches which:

i. uses energy criteria possibly in conjunction with strength criteria, and
ii. takes into account failure propagation through the structure.

Concrete is used as rigid pavement in road construction for durability; however, early crack if not prevented will results in structural failure of the road and does reduces its service life. A rigid pavement structure is the one having a layer of concrete. It composed of a hydraulic cement concrete surface course and underlying base and sub-base courses (if used) (Russel and Lenz, 2011). The surface course (concrete slab) is the stiffest layer and provides the majority of strength. Rigid pavements are used where the bearing capacity of the underlying soil layers is insufficient to withstand the cumulative wheel loads of the expected traffic. The use of concrete in rigid pavement helps to prevent excess deflection as a result of the compressive loading on it. However, with the nature of concrete during use in conjunction with its fracture mechanism, cracks pose a threat to the durability of rigid pavement when left unchecked. Vepa and George (1997) studied the deflection responses of cracked pavement under a series of increasing loads, assuming linear and nonlinear behavior of base, subbase, and subgrade materials, computed and compared. In their study, model and a synthetic deflection database was developed relying on a fractional factorial design layout in which thicknesses, layer modulo, and cracks were also allowed to vary over a range. Thus, this research investigates the crack mechanism of different concrete grades under compressive loading and its suitability as rigid pavement.

3 MATERIALS AND METHOD

3.1 Materials

The materials utilized for this research work were chosen carefully to meet with standard requirement, the Ordinary Portland Cements (Grade 32.5) with three different brands of cements in Nigeria namely; Dangote (Type A), Elephant (Type B) and Bua (Type C) were purchased from Akure Township. The coarse aggregate of size 5-16 mm made was obtained from Johnson quarry and fine aggregate (river sand) free from deleterious materials was sourced from Ala river both in Akure township Nigeria. Potable water used for the production and curing of concrete was gotten from Concrete Laboratory, Civil and Environmental Engineering Department Federal University of Technology, Akure.

3.2 Method

Specified proportions of each material consisting of river sand of maximum size 5 mm and coarse aggregate of size 5-16 mm was used. Using a mix design ratios of 1: $1\frac{1}{2}$: 3 (M_{20}), 1: 2: 4 (M_{15}) and 1: 3: 6 (M_{10}) and water cement ratio of 0.63, a total of one hundred and eight concrete cubes of sizes 150 mm x150 mm x150 mm were casted. This consist of 36 cubes each for Type A, Type B and Type C cement respectively; each having of 3 cubes per mix ratio. The cubes were cured to allow it gain maximum strength, the cubes was crushed after 7, 14, 21 and 28 days respectively to determine the compressive strength and bulk density. Compressive strength test was performed on the cube samples using 1500 kN compressive testing machine shown in Figure 1. The cubes were subjected to compression load at a constant rate while the maximum load at failure was recorded. The compressive strength is determined by dividing the load (force) with the area of the tested cubes while, the crack width was measured using microscopic technique. Several tests were performed in accordance to the standard specifications as shown in Table 1.

Fig 1: ELE Compression Testing Machine

Table 1: Tests carried out on the materials

Materials	Tests	Specifications
	Particle size distribution	**ASTM C136/C136M**
Coarse Aggregate	ACV	BS 812-110:1990, ASTM C131
	AIV	BS812-112:1990
Hardened Concrete	Compressive strength	ISO 9001 (2008)
	Crack width measurement	Microscope
	Yield period measurement	Stop Watch

4 RESULTS AND DISCUSSIONS

Figure 2 is the graph of particle size distribution of the fine aggregate, Tables 2 is the results of result of varying tests conducted on concrete in both fresh and hardened state.

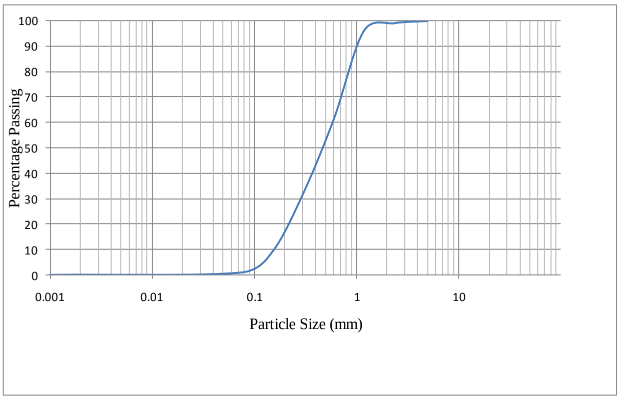

Fig 2: Particle Size Distribution of the Fine Aggregate

From the Particle Size Distribution (PSD) curve in Figure 2; Effective size = D10 = 0.15 mm, D60 = 0.6 and the Uniformity Coefficient $C_u = \frac{D60}{D10}$

Therefore, $C_u = \frac{0.6}{0.15} = 4.00$

The Fineness modulus of the sand $= \frac{301.84}{100} = 3.02 <$ 3.20(Suitable for concrete works)

Therefore means that the sand is well graded.

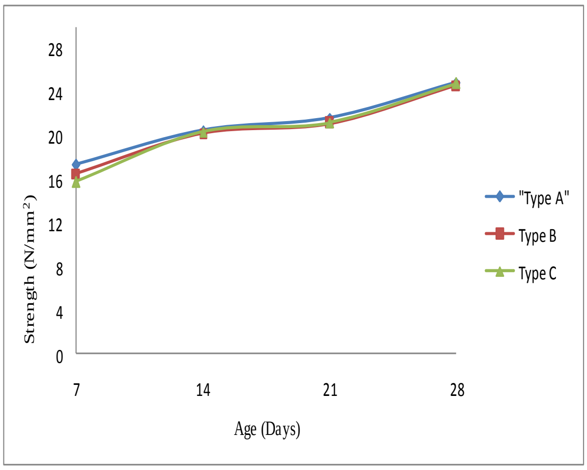

Fig 3: Strength versus Age for Concrete Grade M20

Table 2: Tests on Aggregate, Fresh Concrete and Hardened Concrete

Test on Fine Aggregate			
Specific gravity	2.65		
Natural moisture content	9.45%		
Silt/Clay content	9.3%		
Bulk density	1730 kgm^{-3}		
Test on Coarse Aggregate			
ACV	25.4%		
AIV	19.4%		
Gs	2.68		
Bulk Density	1760 kgm^{-3}		
Test on Cement			
	Type A	**Type B**	**Type C**
Initial setting time (mins)	10	10	10
Final setting time (mins)	630	635	638
Soundness test (%)	4.17	4.19	4.18
Fineness test (%)	5	5.2	5.5
Slump (mm)			
Grade	**Type A**	**Type B**	**Type C**
M_{20}	40	30	40
M_{15}	30	33	30
M_{10}	35	32	35
Compacting Factor			
Grade	**Type A**	**Type B**	**Type C**
M_{20}	0.94	0.91	0.99
M_{15}	0.92	0.95	0.95
M_{10}	0.92	0.92	0.94
Air Entrainment			
Grade	**Type A**	**Type B**	**Type C**
M_{20}	1.5	1.8	1.8
M_{15}	1.7	1.7	1.8
M_{10}	1.6	1.7	1.7

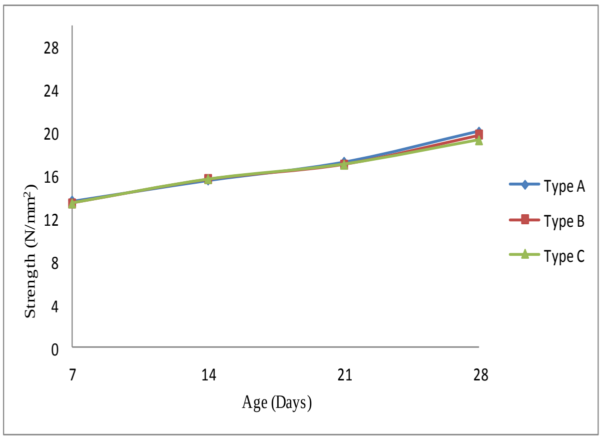

Fig 4: Strength versus Age for Concrete Grade M_{15}

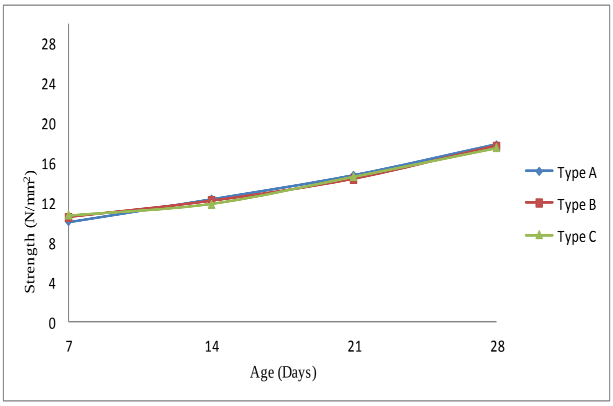

Fig 5: Strength versus Age for Concrete Grade M_{10}

It can be noticed from the graphs above for the three samples that the strength increases as the curing age increases which implies that curing of concrete plays a vital role in giving it the required strength. The trend also shows that for mix ratio 1:1.5:3 at seven, fourteen, twenty one and twenty eight days respectively that sample 1 gives the optimum values of 17, 21, 22 and 25 N/mm^2 followed by sample 3 and 2 respectively. It can be noted that sample 2 has a compressive strength greater than that of sample 3 at seven days (i.e. 17 N/mm^2 > 16 N/mm^2), this implies that sample 3 cement concrete gain more strength faster than sample 2 as the curing age increases.

Table 3: Specified Compressive Strengths for Concrete Grades

Concrete Grade	Strength N/mm^2 at 7 days	Strength (N/mm^2) at 28 days
M_{15}	10	15
M_{20}	13.5	20
M_{25}	17	25
M_{30}	20	30
M_{35}	23.5	35
M_{40}	27	40
M_{45}	30	45

Source: International Organization for Standardization 9001 (2008)

Comparing the values above for the three samples of cement with the standard in Table 3.0, it shows that the samples tested falls between grades M_{15} to M_{25} at 7 days and 28 days, and this is due to different mix ratio used for the samples which implies that the sample tested satisfied the minimum required strength for rigid pavements.

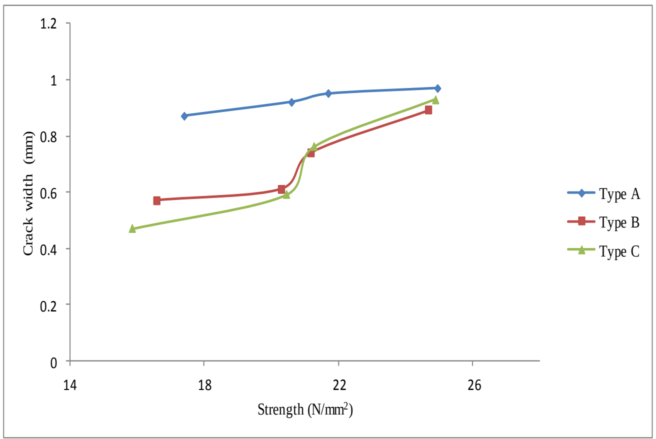

Fig 6: Crack width versus Strength for Concrete Grade M_{20}

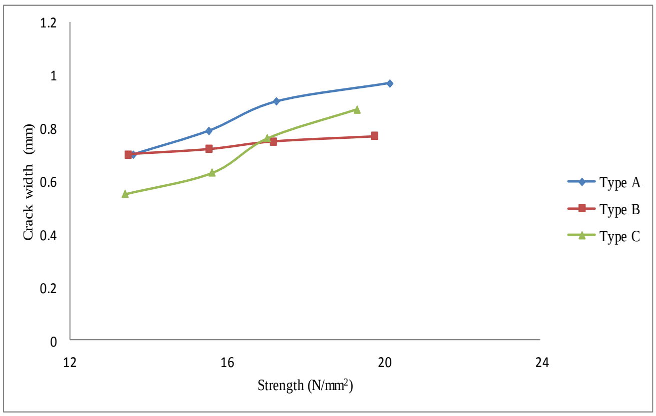

Fig 7: Crack width versus Strength for Concrete Grade M_{15}

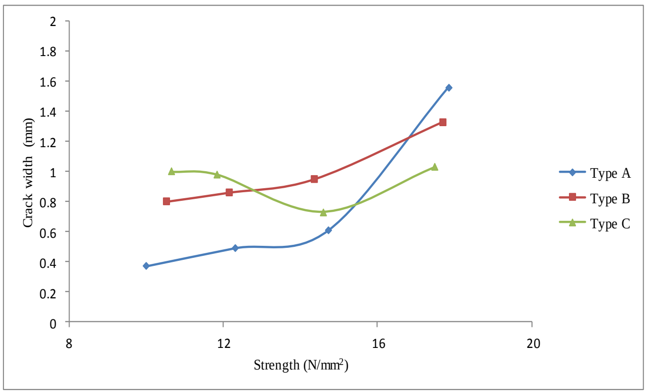

Figure 8: Crack width versus Strength for Concrete Grade M_{10}

It can be noticed from Figures 6, 7 and 8, that the crack width increases as the strength increases In Figure 8, concrete grade M_{10} exhibit a sharp drop between 10 N/mm^2 and 14.7 N/mm^2 and increased again at 15 N/mm^2. The crack width-strength curve for concrete grade M_{20} and M_{15} follows the same trend of linearity while, concrete grade M_{10} show more nonlinearity. The crack width for M_{20} and M_{15} at peak compressive strength is about 1.0 mm which is permissible for a normal concrete; however, concrete grade M_{10} has a crack width of 1.6 mm.

5 CONCLUSION

The study investigated the nature of progressive crack growth in plain concrete used in rigid pavement under compressive strength, and the suitability of the concrete grades for rigid pavement construction. The following conclusions concerning the behavior of plain concrete under continuous compressive loading were drawn:

i. The crack width increases with increase in the strength of concrete and the curing age of concrete;

ii. Maximum compressive strength value of 24.96 N/mm^2, 24.67 N/mm^2 and 24.89 N/mm^2 respectively was obtained for concrete M20 for Type A, Type B and Type C cement at the 28 day. A corresponding crack width of 0.97 mm, 0.89 mm and 0.93 mm was obtained while; a yield period of 57.66 sec, 58.33 sec and 53.33 was obtained respectively. Comparing with the International Organization for Standardization, concrete grade M_{20} any of the cement types is suitable for the construction of rigid pavements with heavy traffic volume while M_{15} is recommended for low traffic volume

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